TR-240: NEAR REAL-TIME RUNOFF ESTIMATION USING SPATIALLY DISTRIBUTED RADAR RAINFALL DATA

A Thesis

by

JENNIFER LYN HADLEY

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2003

Major Subject: Forestry

Texas Water
Resources Institute
make every drop count

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Approved as to style and content by:

Raghavan Srinivasan (Chair of Committee)	Robert Knight (Member)
X. Ben Wu (Member)	C.T. Smith (Head of the Department)

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ABSTRACT

Near Real-Time Runoff Estimation Using Spatially Distributed Radar Rainfall Data.

(December 2003)

Jennifer Lyn Hadley, B.S., Texas A&M University

Chair of Advisory Committee: Dr. Raghavan Srinivasan

The purpose of this study was to evaluate variations of the Natural Resources Conservation Service (NRCS) curve number (CN) method for estimating near real-time runoff for naturalized flow, using high resolution radar rainfall data for watersheds in various agro-climatic regions of Texas. The CN method is an empirical method for calculating surface runoff which has been tested on various systems over a period of several years. Many of the findings of previous studies indicate the need to develop variations of this method to account for regional and seasonal changes in weather patterns and land cover that might affect runoff. This study seeks to address these issues, as well as the inherent spatial variability of rainfall, in order to develop a means of predicting runoff in near real-time for water resource management. In the past, raingauge networks have provided data for hydrologic models. However, these networks are generally unable to provide data in real-time or capture the spatial variability associated with rainfall. Radar networks, such as the Next Generation Weather Radar (NEXRAD) of the National Weather Service (NWS), which are widely available and continue to improve in quality and resolution, can accomplish these tasks. In general, a statistical comparison of the raingauge and NEXRAD data, where both were available, shows that the radar data is as representative of observed rainfall as raingauge data. In this study, watersheds of mostly homogenous land cover and naturalized flow were used as study areas. Findings indicate that the use of a dry antecedent moisture condition CN value and an initial abstraction (I_a) coefficient of 0.1

produced statistically significant results for eight out of the ten watersheds tested. The urban watershed used in this study produced more significant results with the use of the traditional 0.2 I_a coefficient. The predicted results before and during the growing season, in general, more closely agreed with the observed runoff than those after the growing season. The overall results can be further improved by altering the CN values to account for seasonal vegetation changes, conducting field verification of land cover condition, and using bias-corrected NEXRAD rainfall data.

ACKNOWLEDGEMENTS

This thesis would not have been possible without the support, guidance, and contributions of several people. First, I would like to thank Dr. Srinivasan for his support and guidance throughout this research, and for allowing me the opportunity to work in the Spatial Sciences Lab. The experience I have gained through this work has been invaluable. In addition, I would like to thank my committee members, Dr. Robert Knight and Dr. Ben Wu, who have been instrumental in helping me to complete this project. Their guidance both as an undergraduate and graduate student has been greatly appreciated.

I would like to thank the Forest Science Department faculty and staff for all their assistance through the graduate school process. Also, my friends and co-workers at the SSL have been supportive through the past few years on both a personal and professional level. Their friendship has made the time at the lab more enjoyable. I would like to especially thank Mr. Balaji Narisimhan for his unending help and encouragement.

I would also like to thank the group at the Texas Water Resources Institute, including Dr. Allan Jones, Dr. Bill Harris, and Dr. Ric Jensen for their support, encouragement, and funding for this project.

On a personal note, I would like to thank my family, including my parents, parents-in-law, my aunts and uncle, and brother and sister for their unending love, support, and encouragement to continue my education. Without this support I may not have pursued this degree. And lastly, I would like to thank my husband Donnie for his understanding through this trying time and his continued support for my decisions. His patience, faith, and love are appreciated beyond words.

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I. INTRODUCTION

Water availability has become a major issue in Texas in the last several years. Adding to this issue is the expected doubling of the population within the next 50 years, mainly in areas of the state presently without abundant water supplies (Texas Water Development Board 2000). To combat the problems that Texas will face in the future, there has been a move toward active planning and management of water resources. Real-time weather data processing and hydrologic modeling can provide information useful for this planning in addition to flood and drought mitigation, reservoir operation, and watershed and water resource management practices. However, in order to provide this information to managers, it is necessary to first obtain reliable weather data. Rainfall data, in particular, is extremely important in hydrologic modeling because rainfall is the driving force in the hydrologic process.

Raingauge networks are generally sparse and insufficient to capture the spatial variability of rainfall across large watersheds. This is especially true in arid and semi-arid regions, such as west Texas, where most rainfall occurs in short, heavy, localized thunderstorms. It is often difficult to capture such events using the sparsely scattered raingauge networks present today. The dense networks necessary to provide such data are generally available only for experimental or research watersheds. In addition, only a limited number of raingauge networks are currently able to provide data in real-time. The use of data from weather radar systems could help alleviate these problems. One such system is the Next Generation Weather Radar (NEXRAD) of the National Weather Service (NWS), formally known as the Weather Surveillance Radar-1988 Doppler (WSR-88D).

This thesis follows the style and format of the Journal of Soil and Water Conservation.

Weather radars estimate precipitation using remote sensing techniques by transmitting and receiving electromagnetic signals. They provide rainfall data with better spatial and temporal resolution than the current raingauge networks, and this data is available in real-time over large areas. However, radar estimates suffer from several sources of errors, including incorrect hardware calibration and ground clutter contamination, making data quality control for these networks extremely important. Nevertheless, radar rainfall data provides the best real-time, spatially and temporally distributed rainfall estimates available with current technologies.

The purpose of this study was to evaluate several variations of the Natural Resources Conservation Service (NRCS – formerly known as the Soil Conservation Service – SCS) curve number (CN) method for estimating near real-time runoff for naturalized flow, using high resolution radar rainfall data for watersheds in various agro-climatic regions of Texas.

II. OBJECTIVES

The primary objectives of this study were to:

1. Select study areas based on the size of the watershed, land use, soil hydrologic group, rainfall pattern/agro-climatic region, and streamgauge location. In addition, calculate the weighted average CN for all study areas with CN grids at several different resolutions to account for issues concerning spatial variability of soil and land use inputs.
2. Compare traditional raingauge with NEXRAD radar rainfall data on a point by point basis for all chosen study areas. Then evaluate several variations of the NRCS CN method in selected study areas by comparing the modeled runoff for NEXRAD and raingauge data with observed streamgauge data for the entire study period to determine the most appropriate method for estimating runoff in various regions of Texas.
3. Evaluate the intra-annual variability of chosen methods as well as characterize rainfall and runoff across watersheds through statistical analysis.

The first objective of this study was to select test watersheds that were of various size, land use, soil composition, and agro-climatic region, in order to best account for the wide variety of hydrologic conditions throughout the state. However, these sites also required U.S. Geological Survey (USGS) streamgauge monitoring stations at the watershed outlets to provide a means of comparison between model outputs and actual streamflow observations. Also, study areas should have natural, or unregulated flow, *i.e.* these areas should not have reservoirs or other diversions within the watershed boundaries. In addition, the weighted average CN was calculated for each watershed based on CN grids at various resolutions, in order to account for spatial variability of land use and soil inputs.

The raingauge and NEXRAD radar rainfall data was compared on a point by point basis for all watersheds to determine the statistical significance of the NEXRAD rainfall data as compared with the available raingauge rainfall data. Once these comparisons were made, the NRCS CN method for runoff estimation was modified and tested in each watershed for comparison with observed streamflow.

These modifications included the choice of CN based on antecedent soil moisture condition and the input value for initial abstractions. These models were tested over multiple years, and included the NEXRAD rainfall for 1999 – 2001, as well as historical data from raingauge locations for comparison purposes. Initially, all variations of the CN method and both rainfall data inputs were used to determine the significance of each alternative. Once this was determined for the initial sample set, the more effective alternatives were applied to the remaining study areas.

The final objective of this study was to compare the seasonal accuracy of the chosen runoff estimation methods. In addition, a statistical analysis of flow events, with ranked natural rainfall to runoff pairs was completed. These statistical comparisons helped to identify issues associated with runoff estimation.

III. RELEVANT LITERATURE

3.1 NRCS Curve Number Method

In the 1950's the SCS developed the CN method for estimating runoff in ungaged watersheds. The methodology for this model is outlined in the SCS National Engineering Handbook, Section 4 (NEH-4) (SCS 1972). The model estimates runoff based on rainfall depth and a CN variable. Curve number is a unit-less variable that is assigned based on land cover and soil hydrologic group/ soil texture. CNs range from 0 – 100 and runoff increases with CN value. Average values for an area can be found in CN tables in the NEH-4 manual.

The CN method is widely used by hydrologist and engineers for watershed modeling, and has been used as a simple watershed model and incorporated into various computer models worldwide (Woodward et al. 2002; Hawkins et al. 2002). Although this is an accepted method for runoff estimation, several studies have indicated that the method should be evaluated and adapted to regional agro-climatic conditions.

First, because the variables used in the model are based on overall watershed characteristics, it should not be used as a point observation model, but rather as an expression of net watershed performance (Van Mullem et al. 2002). Hawkins (1998) and Hawkins and Woodward (2002) state that CN tables should be used as guidelines and that actual CNs and their empirical relationships should be determined based on local and regional data. This is supported by Van Mullem et al. (2002). They state that the direct runoff calculated by the CN method is more sensitive to the CN variable than rainfall inputs. This would suggest an increased need for field verification of land cover type and condition before CN assignment.

Price (1998) determined that CN could be variable due to seasonal changes in vegetation and rainfall pattern. The study evaluated the seasonal variability in CN values calculated from event data in 270 watersheds across the U.S. The study indicated that there was little seasonal variation in CN for agricultural and grassland dominated watersheds; however, there was noticeable change in CN value for forested watersheds. This finding was based on lower average CN and high serial correlation coefficient values. Van Mullem et al. (2002) also note seasonal variations in CN values. Their findings indicate that this may be more obvious in humid areas, and is evidenced by higher CNs during the dormant season and lower CNs during the summer months, or growing season. This study also indicated that the seasonal change in CNs in forested areas may be attributed to leafing stages of the vegetation.

In addition, Ponce and Hawkins (1996) stated that values for initial abstractions (I_a) could be interpreted as a regional parameter to improve runoff estimates. According to Hawkins et al. (2002) and Jiang (2001) an I_a value of 0.05 was generally a better fit than a value of 0.2. In 252 of 307 cases, a higher r^2 was produced with the 0.05 value.

Walker et al. (1998) used baseflow as a measure of watershed wetness in determining the CN value for modeling applications in mildly-sloped and tile-drained watersheds in east-central Illinois. Their findings suggested that the use of baseflow, rather than antecedent moisture condition, provided better results in runoff estimations. They also suggested that future research include a study of alternative measures of watershed wetness and assumptions concerning I_a.

The accuracy of hydrologic models depends heavily on the accuracy of input data, especially rainfall. In addition, for hydrologic models such as the NRCS CN method, there is a need to determine the most accurate variable inputs based on regional conditions. This study seeks to incorporate the use of NEXRAD radar rainfall into variations of the NRCS curve number method in an attempt to better represent the spatial variability of rainfall and produce more accurate runoff estimates.

3.2 NEXRAD

A number of previous studies have evaluated all stages of NEXRAD rainfall data in relation to raingauge data for corresponding areas (a more detailed description of NEXRAD stage data will follow). Lott and Sittel (1996) compared Stage III NEXRAD rainfall data with a network of 220 raingauges for rainfall events from 1994 to 1995. In 80% of the raingauge locations, radar underestimated rainfall totals. Anagnostou et al. (1998) compared Stage I data from the Tulsa, Oklahoma radar with 240 raingauge stations. Although the correlation coefficient (*CC*) at several locations was less than 0.30, the *CC* for most of the locations in the study ranged from 0.30 to 0.95. Their findings suggest that Stage III bias-adjusted data was a better comparison with raingauge data. In addition, this study indicates a potential for a seasonal mean-field bias (defined as the ratio of difference in total precipitation depth between radar and raingauge to raingauge total precipitation (Bedient et al. 2000)). This bias was lower during warmer season months than during the colder season months.

Other studies found underestimation due to terrain blockage (Westrick et al., 1999) and extremely high rainfall events (Baeck and Smith 1998). Baeck and Smith (1998) noted that the data processing system used at the time was responsible for the extreme underestimation of rainfall totals, in some instances by a factor of more than five. Legates (2000) derived a reflectivity-rainfall rate relationship (Z-R relationship) to address issues in radar calibration with the use of raingauge data. This relationship increased rainfall estimates, which more closely matched observed rainfall. This same study indicated that standard Z-R relationships used in data processing tend to overestimate light rainfall events and underestimate heavy rainfall events. Jayakrishnan (2001) compared NEXRAD and raingauge data in the Texas-Gulf basin. This study suggests that based on improved data processing algorithms and on-going developments, after 1998, NEXRAD was more accurate when compared to raingauge data. In addition, this data did not suffer from the underestimation seen in the past. The study states that raingauges with more than 20% underestimation dropped from 75% in 1995 to 6% in 1999.

These studies highlight the need for accurately calibrated radar data and suggest that there have been improvements in data processing over the history of this technology. Still, there is a need for comparison between NEXRAD and raingauge data in order to eliminate ground clutter or other sources of data contamination (Sauvageot 1992; Legates 2000). However, based on technological advances and the spatial and temporal variability that radar can capture, hydrologic studies have begun to incorporate NEXRAD as an input to various models.

3.3 Hydrologic Modeling with NEXRAD

Bedient et al. (2000) used NEXRAD as an input to the HEC-1 model to develop a flood forecasting system in the Brays Bayou watershed in Houston, Texas. Their findings show that NEXRAD rainfall estimates performed as well as or better than raingauge data in their model. This data is now being used in a near real-time flood warning system application. Ogden et al. (2000) used NEXRAD rainfall data with the CASC2D model to evaluate hydrologic prediction of extreme events in urban environments in the Spring Creek watershed in Fort Collins, Colorado. They found that radar rainfall was useful in hydrologic modeling when gauge adjusted. Otherwise the radar underestimated the rainfall totals in extreme events. Using the uncalibrated rainfall data, the estimated rainfall volume for the watershed study area was 42% less than the raingauge reference rainfall volume.

IV. MATERIALS AND METHODS

The main goal of this study was to evaluate various alternatives of the NRCS CN method for estimating runoff, using high resolution radar rainfall data for watersheds in various agro-climatic regions of Texas. The CN method calculates runoff based on the land cover and soil hydrologic group, as well as the rainfall depth for the day. Basically, variations in land cover types and the infiltration rate of the associated soil, as well as the amount of rainfall at any given time, will change the rate at which rainfall becomes surface runoff.

The input data needed for the CN method includes land cover and condition and soil hydrologic group data for CN assignment, and weather data for the runoff equation calculation. For this study, a fair condition was assumed due to the difficulty in obtaining such information for a large area in a spatially consistent manner. In addition, the observed streamflow data is needed as a reference to determine the statistical significance of the runoff estimates produced by these calculations. Once this data was collected, the study areas were identified based on a variety of criteria, including size, land use, rainfall pattern/agro-climatic region, and streamgauge location.

Each of the delineated watersheds is composed of subbasins which are 4 km x 4 km pixels, corresponding to the NEXRAD grid. After some additional data analysis and processing, as well as a comparison of raingauge to NEXRAD rainfall data, runoff estimates were generated for each study area.

4.1 Input Data

4.1.1 Land Cover Data. The 1992 USGS National Land Cover Data (NLCD) was used as the land cover dataset for this study. This dataset was derived from Landsat 5 Thematic Mapper (TM) imagery through a process of unsupervised clustering. Clusters were then placed into one of 21 thematic classes similar to the Anderson Level II land use classification scheme (Anderson et al. 1976). The accuracy assessment process has not been completed for Region 6, which includes Texas; however, this is the most detailed state-wide coverage available at the current time. The scale for this dataset is 1:24,000 (30 m resolution).

Land cover information was used in selecting study areas and as an input to the various runoff equations to assign average CN values. Only areas with a homogenous/dominant cover or similar CN assignments were used in this study, which simplified the modeling process by reducing the number of variables.

The dominant land use was determined with the use of ESRI's ArcView 3.x software Tabulate Area function. This function identifies the area of land use within each user identified zone, in this case the watershed boundary. This information was then processed to determine the percentage of each cover type.

4.1.2 Soil Data. The U.S. Department of Agriculture (USDA)-NRCS State Soil Geographic (STATSGO) Database, at a 1:250,000 scale (250 m resolution), was used to determine the soil hydrologic group. This dataset was created by generalizing more detailed soil survey maps or with the use of auxiliary data and Landsat imagery. The maps are delineated into map units of dominant soil type and may consist of 1-21 different components. This dataset is designed to support regional, multi-state, state, or river basin resource planning, management, and monitoring; however, it offers the only detailed state-wide coverage available at the current time.

Soil hydrologic group information helped to determine runoff potential for a particular study area as an input to runoff equations for CN assignment. For the purposes of this study, soils were placed in one of four classes based on the infiltration rate (Wurbs and Sisson 1999):

Group A: deep sand, deep loess, aggregated silts (infiltration 0.30 – 0.45 in/hr)
Group B: shallow loess, sandy loam (infiltration 0.15 – 0.30 in/hr)
Group C: clay loams, shallow sandy loams, soils low in organic content, soils high in clay content (infiltration 0.05 – 0.15 in/hr)
Group D: soils that swell significantly when wet, heavy plastic clays, certain saline soils (infiltration 0 – 0.15 in/hr)

The STATSGO soils database was reclassified to a four-class grid based on the dominant soil hydrologic group and resampled to a 30 m grid in order to be consistent with the NLCD dataset.

4.1.3 Streamflow Data. Measured streamflow data was obtained from the USGS for comparison purposes. Streamgauge data for each watershed outlet was downloaded from the USGS website and processed through a filter program to separate the baseflow from the runoff portions of total streamflow.

Total streamflow is composed of baseflow (shallow ground water discharge to streams) and surface runoff. In order to make comparisons between streamgauge measured flow and the runoff estimates generated in this study (NRCS CN method provides only direct runoff after a rainfall event), it was necessary to determine the portion of streamflow that could be attributed to surface runoff.

The filter program used in this study was obtained from the Soil and Water Assessment Tool (SWAT) website (http://www.brc.tamus.edu/swat). Although there are a number of filter programs available, according to Arnold et al. (1995) and Arnold and Allen (1999), this program is comparable to other automated separation techniques, and had 74% efficiency when compared to manual separation. In addition, this program is used with the SWAT program internationally, and has been tested on a wide variety of hydrologic systems.

This program works much like the filtering of high frequency signals in signal analysis. Low frequency signals would represent baseflow, where as high frequency signals would represent runoff (Arnold et al. 1995). After separation, baseflow can be subtracted from total streamflow, which provides the portion of flow that can be attributed to runoff.

This data was used to evaluate the accuracy of model results; therefore, only sites with adequate historical data were used. For this study, a period of 20-30 years with corresponding weather data was considered adequate to account for rainfall variability and the hydrologic cycle. Lastly, because the runoff algorithms used in this study do not account for reservoirs or other diversions, only sites with natural, or unregulated, flow were used. This allowed for a direct comparison of runoff estimates to measured streamflow data.

4.1.4 Weather Data. NEXRAD data was obtained from the West Gulf River Forecasting Center (WGRFC) of the National Weather Service (NWS). Only data for the 1999 – 2001 time period was used in this study based on findings by Jayakrishnan (2001), citing improved NEXRAD data quality and accuracy in recent years.

Twenty-three radar stations in Texas, Louisiana, New Mexico, and Colorado make up the Hourly Digital Precipitation (HDP) network utilized by the WGRFC. The raw data obtained from the HDP network is considered Stage I output, and is available in 4 km x 4 km resolution grids, with cells identified by the Hydrologic Rainfall Analysis Project (HRAP) number. Stage I data is then corrected using a bias adjustment factor based on available one-hour raingauge reports. The resulting correction is available as Stage II data. Finally, Stage II data for all radars are combined into one map with ground truth data from gauge stations, and overlapping areas are averaged together. The result is multi-sensor Stage III adjusted data, which will be used in this study. In this process, the combining and averaging of overlapping data, or mosaicking, helps to compensate for the overestimation or underestimation of individual radars (Jayakrishnan 2001). More detailed information about NEXRAD products and processing algorithms can be found in Crum and Alberty (1993), Klazura and Imy (1993), Smith et al. (1996), and Fulton et al. (1998).

Daily rainfall data from raingauge stations in and around the chosen study areas were collected from the National Climatic Data Center (NCDC) of the NWS. This data corresponds to the available streamflow data collected from the USGS for each watershed, and was used as an input for runoff estimation.

The nearest raingauge and NEXRAD stations were identified for each subbasin within the delineated watersheds using ESRI's ArcGIS 8.x software. Missing data were replaced with data from the next nearest station, and the data was used to generate daily precipitation files for the watersheds for each year.

The runoff results based on NEXRAD and raingauge data were compared to USGS streamflow data to determine estimation accuracy. In addition, a point comparison of raingauge and NEXRAD daily rainfall data was completed for each station in this study for all three years.

4.2 Study Areas

Ten subwatersheds of varying size, in four river basins, throughout different agro-climatic regions of Texas (Figure 4.1), were used in this study in order to account for the wide variety of hydrologic conditions throughout the state (Table 4.1). These areas were chosen based on the dominant land use, soil hydrologic group, and streamgauge location. The time period for streamgauge data was also a factor in determining these study areas. In addition, all point source locations were identified with the use of a point source permitting system database obtained from the Texas Commission on Environmental

Quality (TCEQ). Watersheds with a number of minor facility class locations, a major facility class location, or any location at the identified outlet of the watershed were omitted from further analysis.

Figure 4.1. Major Land Resource Area (MLRA) boundaries in Texas.

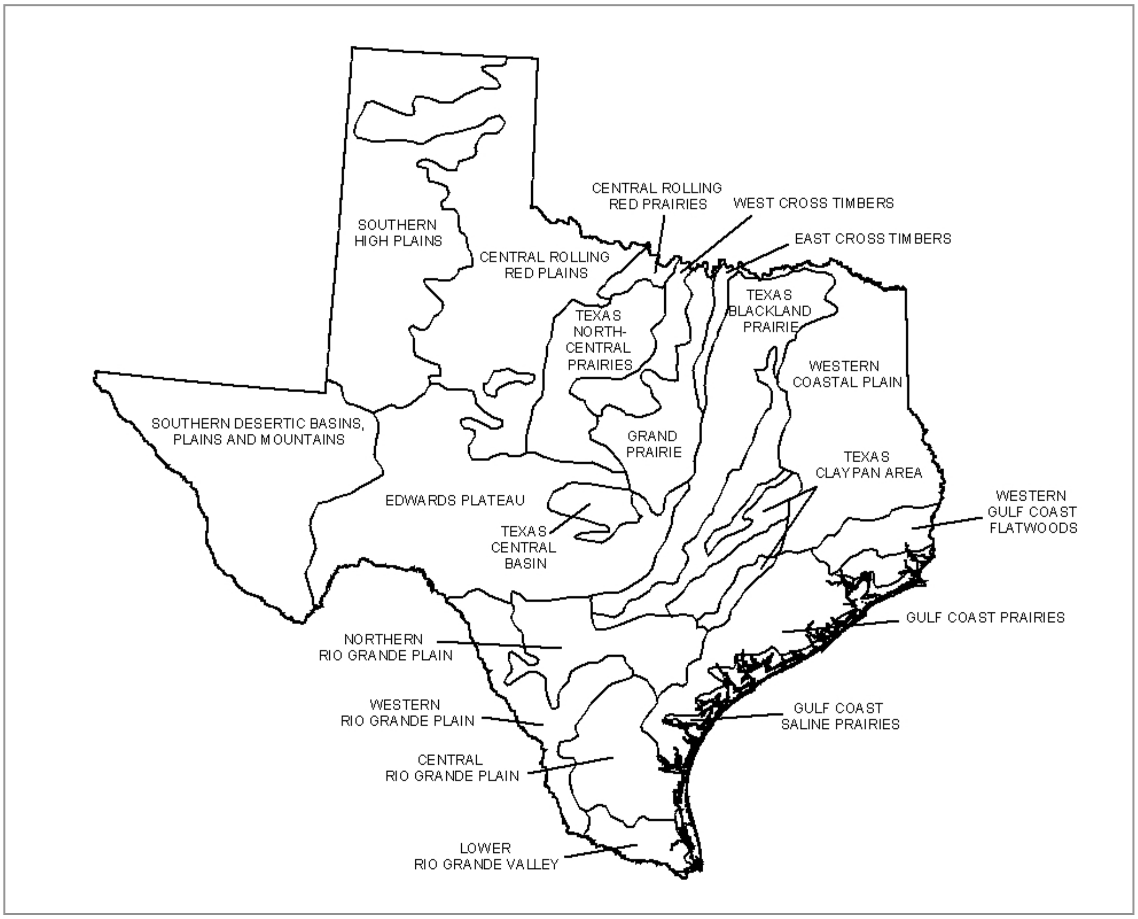


Table 4.1. Description of watershed study areas chosen for analysis.

Watershed	USGS Streamgauge	Stream Name	MLRA	Drainage Area (km^2)	Rainfall Range (mm)	Major Land Cover Characteristics
Trinity-1	8042800	West Fork Trinity River	Texas North Central Prairies	1,769	550 - 750	56% herbaceous rangeland; 17% shrubland; 13% deciduous forest
Trinity-2	8065800	Bedias Creek	Texas Claypan	831	750 - 1,075	76% improved pasture and hay
Trinity-3	8066200	Long King Creek	Western Coastal Plains	365	1,025 - 1,350	80% forested; 15% improved pasture and hay
Red-1	7311600	North Wichita River	Rolling Red Plains	1,399	500 - 750	33% herbaceous rangeland; 40% row crops; 18% shrubland
Red-2	7311783	South Wichita River	Rolling Red Plains	578	500 - 750	60% herbaceous rangeland; 28% shrubland
LCR-1	8144500	San Saba River	Edwards Plateau	2,940	375 - 750	71% shrubland; 21% herbaceous rangeland
LCR-2	8150800	Beaver Creek	Edwards Plateau	557	375 - 750	40% shrubland; 40% evergreen forest
LCR-3	8152000	Sandy Creek	Texas Central Basin	896	625 - 750	41% evergreen forest; 33% shrubland; 16% herbaceous rangeland
SA-1	8178880	Medina River	Edwards Plateau	850	375 - 750	60% forest; 20% shrubland; 14% herbaceous rangeland
SA-2	8178700	Salado Creek	Edwards Plateau / Texas Blackland Prairie	355	375 - 1,150	50% forest; 32% urban; 10% shrub and herbaceous rangeland

Once watershed boundaries and flow direction were identified, USGS streamgauges were used to aggregate the subbasins and define outlets for subwatersheds. Only streamgauges with records corresponding to weather data used in this study were used in this delineation process. In addition, no subwatersheds were delineated in areas with reservoirs in the upper reaches of the stream or major point source facilities. The drainage area for the streamgauge was matched to the drainage area above the gauge to within plus or minus ten percent to determine subwatershed boundaries.

After the subwatersheds were delineated, the dominant land use was determined using ESRI's ArcView 3.x software Tabulate Area function. Only subwatersheds with homogenous/dominant cover or similar CN values were used in this study. Ten of these subwatersheds were chosen as the basic watershed study areas.

Of the ten watersheds chosen for this study, three are located in the Trinity River Basin, two in the Red River Basin, three in the Lower Colorado River Basin, and two in the San Antonio River Basin (Figure 4.2).

4.2.1 Trinity River Basin. The three watersheds in the Trinity River Basin fall within three separate MLRA regions of the state (Figure 4.3).

The largest watershed (Trinity-1) is located within the Texas North Central Prairies Region. It drains a 1,769 km^2 area and is composed of 56% herbaceous rangeland, 17% shrubland, and 13% deciduous forest.

Figure 4.2. Texas river basin boundaries.

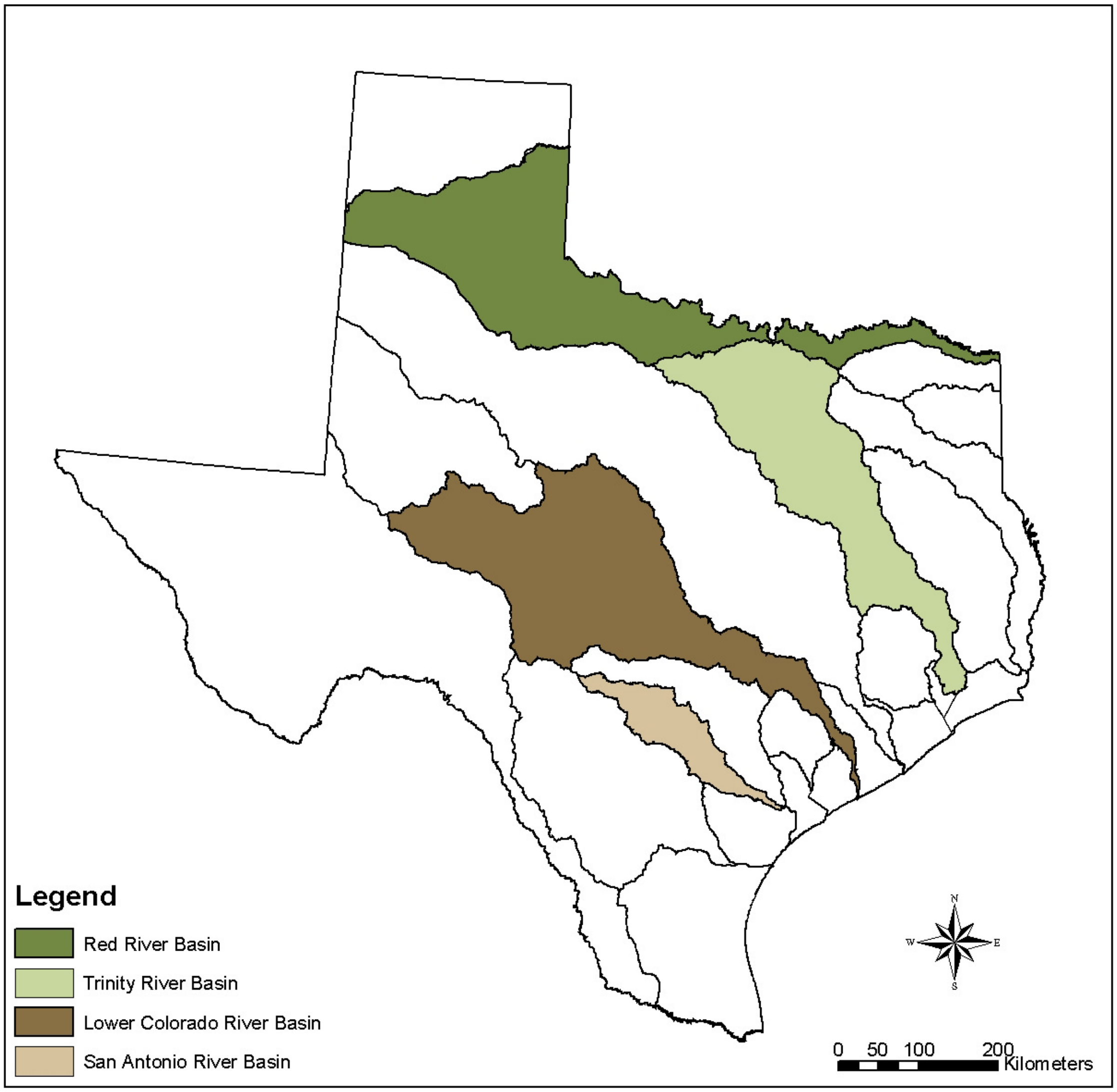
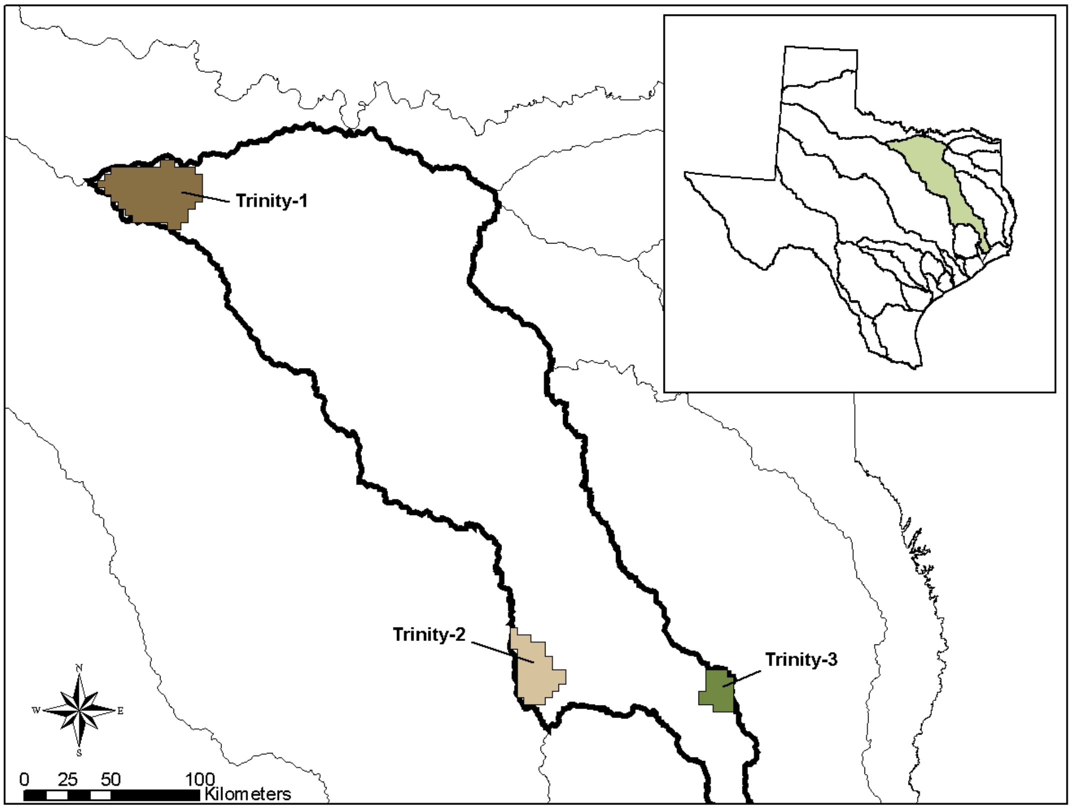


Figure 4.3. Trinity River Basin watershed boundaries.



The Texas North Central Prairies region is almost all ranches and farms and supports mainly savannah type vegetation. It is composed of nearly 80% native range and pastureland and scrub oak forests. An additional 15% of the area is composed of cropland, mainly wheat, oats, cotton, and grain sorghum. The average elevation in the region ranges from 200-700 m. Average annual rainfall ranges from 550-750 mm, with maximum rainfall in the spring and fall. Average annual temperatures range from 18-19º C (NRCS 1997).

The second largest watershed (Trinity-2) is located in the Texas Claypan Area. It covers 831 km^2 and is composed of 76% improved pasture and hay.

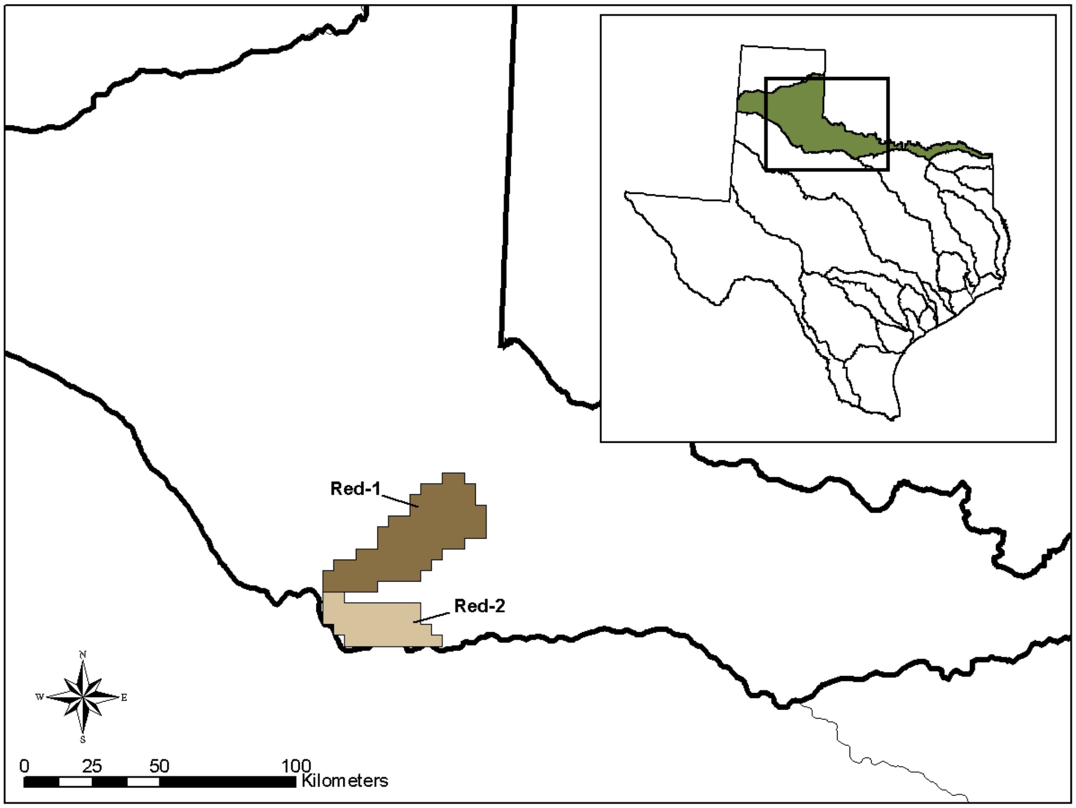
This region is mainly farmland used for pasture and range. About half is in fertilized, improved pasture and much of the rangeland has been overgrazed. Cropland is mainly grain sorghum, and about a third of the farmland is in wood lots. Remaining acreage is native and annual grasses. The area supports a variety of legumes, forbs, shrubs, and woody vines, with mixed pine-hardwood forests in the south and east, and hardwood forests in the bottomland areas. The average elevation in the region ranges from 50-200 m. Average annual rainfall ranges from 750-1,075 mm, with maximum rainfall coming in winter and spring. The average temperature ranges from 18-22º C, and increases from north to south (NRCS 1997).

The smallest of the Trinity watersheds (Trinity-3) is found in the Western Coastal Plains Region. It is approximately 365 km^2 in size, and is composed of 80% forested area, with an additional 15% in improved pasture and hay.

The Western Coastal Plains Region is 50-75% forest or woodland, and is dominated by pine-hardwood forests. Lumber and pulp wood production is important to the region, and land that is cleared is mainly used for improved pasture and hay. Only about one-sixth of the area is used for cropland. Elevation in the region ranges from 25-200 m. Annual rainfall ranges from 1,025-1,350 mm, increasing from northwest to southeast. The maximum rainfall occurs in the spring and early summer with the minimum occurring in the late summer and fall. Average annual temperature ranges from 16-22º C (NRCS 1997).

4.2.2 Red River Basin. The two watersheds within this basin are located in the Central Rolling Red Plains Region of Texas. The larger of the two (Red-1) is composed of 50% shrub and herbaceous rangeland and 40% row crops, and drains approximately 1,399 km^2. The smaller watershed (Red-2) drains approximately 578 km^2, and is composed of 60% herbaceous rangeland and 28% shrubland (Figure 4.4).

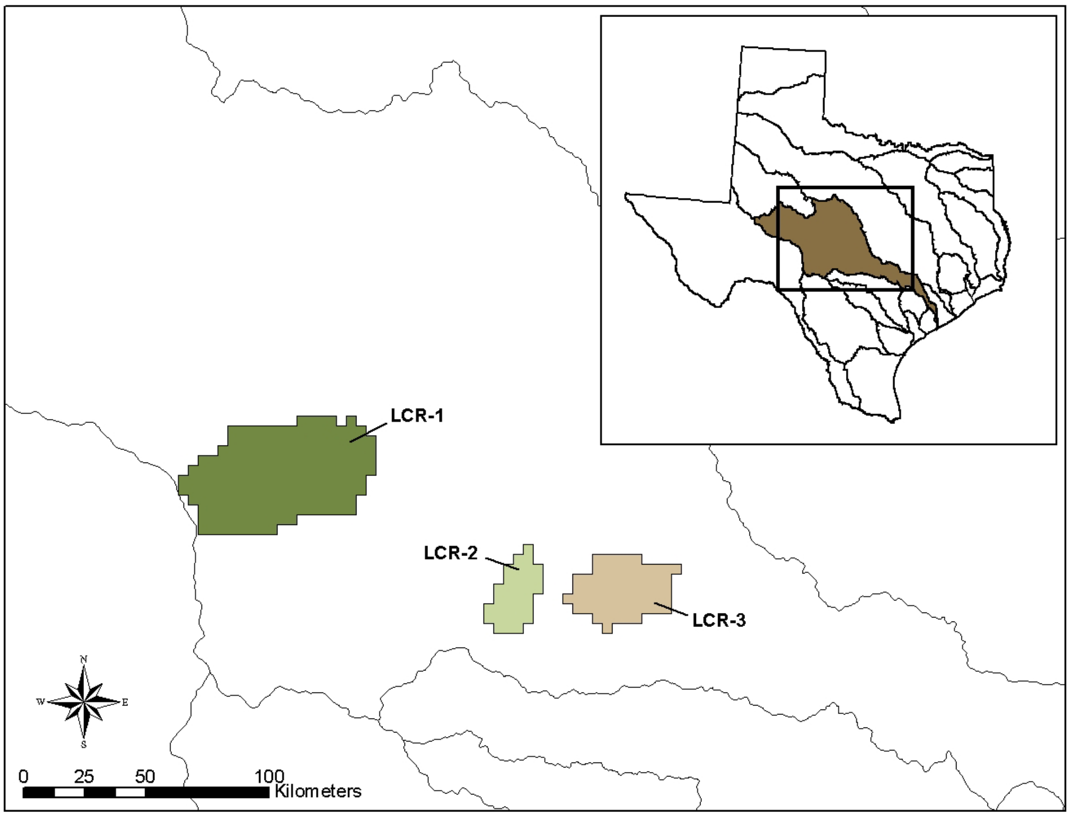
Figure 4.4. Red River Basin watershed boundaries.



According to the NRCS major land resource area (MLRA) description, the Central Rolling Red Plains are composed of 60% rangeland and 35% cropland, and supports mostly mid and tall grasses. Nearly all of the area is used in farming or ranching, and ranges and pastures are generally grazed by beef cattle. Major crops include grain sorghum and winter wheat, and cotton in the south. Elevation in this region ranges from 500-900 m, increasing from east to west. Average annual rainfall ranges from 500-750 mm, increasing from west to east, with maximum rainfall in the spring months and minimum rainfall in the winter months. Average annual temperatures in the region range from 14-18º C (NRCS 1997).

4.2.3 Lower Colorado River Basin. Of the three watersheds in this basin, two are located in the Edwards Plateau region of Texas, and one in the Texas Central Basin (Figure 4.5).

Figure 4.5. Lower Colorado River Basin watershed boundaries.



The largest watershed in this basin (LCR-1) covers approximately 2,940 km^2, and is composed of 71% shrubland and 21% herbaceous rangeland. The smallest watershed in this basin (LCR-2) drains 557 km^2, and is composed of 40% shrubland and 40% evergreen forest. Both of these watersheds are located in the Edwards Plateau Region of Texas.

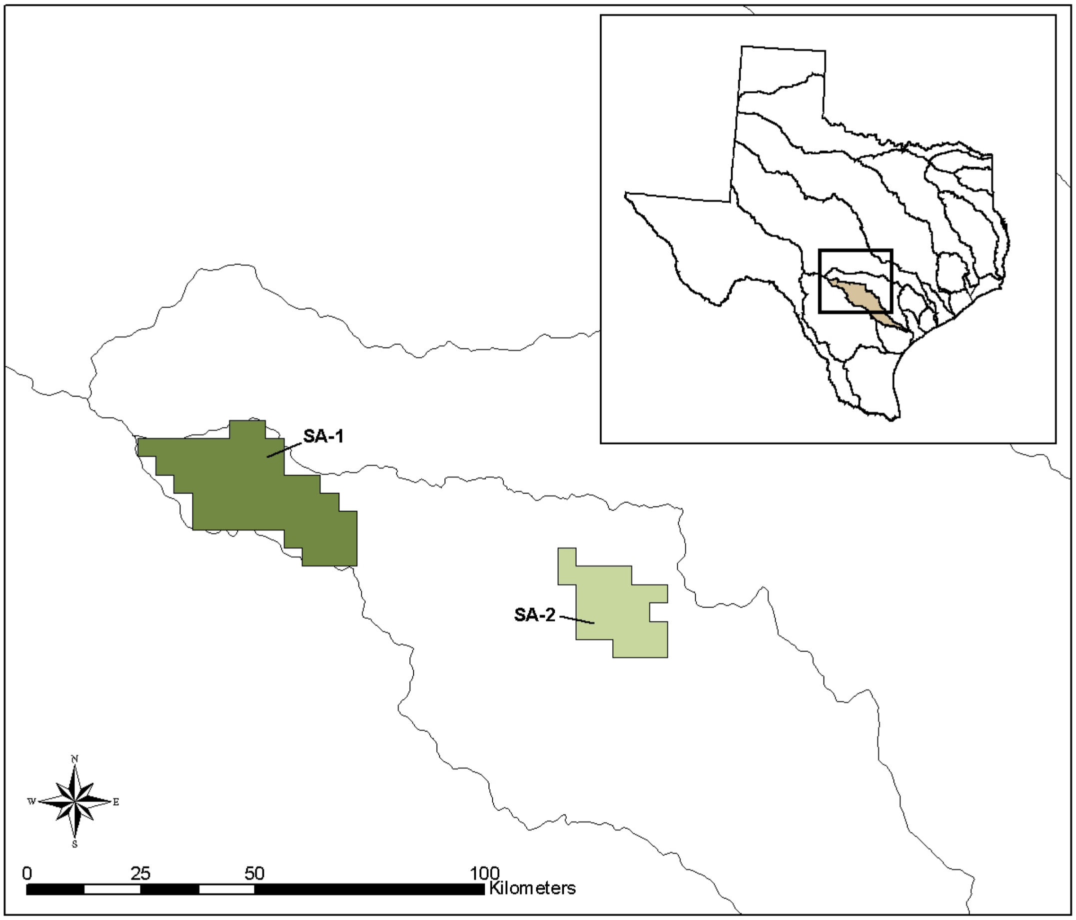
This region is composed mainly of rangeland, which is grazed by beef cattle, sheep, and goats. Cropland is used mainly for improved pasture, hay, and small grains. The area supports vegetation ranging from desert shrubland in the west to mixed oak savannah with mid and tall grasses in the east. The average elevation ranges from 200-500 m on valley floors to 400-1,200 m in the hills and plateaus, and increases from east to west. Average annual rainfall ranges from 375-750 mm, three-fourths of which falls during the growing season. Temperatures range from 18-20º C (NRCS 1997).

The final watershed in the Lower Colorado River Basin (LCR-3) drains 896 km^2. It is composed of mainly forest and rangeland cover, with 41% evergreen forest, 33% shrubland, and 16% herbaceous rangeland. This watershed falls within the Texas Central Basin Region.

This region is mainly rangelands grazed by beef cattle and sheep. Grain sorghum, peanuts, cotton, and other small grains are the main cash crops of the region. In some places, formerly cropped lands are now used as pasture or reverted to rangelands. The region supports mainly mixed oak savannah with mid and tall grass vegetation types. The elevation ranges from 200-300 m on valley floors to 300-400 m in the hills and plateaus. Average rainfall varies from 625-750 mm, with three-fourths falling during the growing season. The average annual temperature ranges from 18-20°C (NRCS 1997).

4.2.4 San Antonio River Basin. In this basin, the largest watershed (SA-1) falls within the Edwards Plateau Region, (this is the same as the LCR-1 and LCR-2 watersheds). The smaller watershed (SA-2) falls between the Edwards Plateau and Texas Blackland Prairie Regions (Figure 4.6).

Figure 4.6. San Antonio River Basin watershed boundaries.



SA-1 drains 850 km^2, and is composed primarily of forested areas (60%), with an additional 20% shrubland, and 14% herbaceous rangeland. The final watershed in this study, SA-2, falls between two MLRA regions, with approximately 60% of its 355 km^2 area in the Edwards Plateau Region and the remaining 40% in the Texas Blackland Prairie Region. In addition, this subwatershed is unique, in that it is composed of 50% forested areas, 10% shrub and herbaceous rangeland, and the remaining 32% is urban area (residential/ industrial/ transportation) in and around San Antonio, Texas. Approximately 60% of this watershed is similar to SA-1, as well as LCR-1 and 2; however, the remaining area falls in the Texas Blackland Prairie Region of Texas.

This region is mainly farmland with increasing urban development. It is composed of approximately 40% cropland, 45% improved pasture or rangeland, and the remainder is urban area with forested areas along rivers and streams. It supports a true prairie vegetation type with some forbs and savannah type vegetation along streams and rivers. The major cash crops are cotton and grain sorghum and the major livestock is beef cattle. Elevation ranges from 100-200 m, from south to north and east to west. Rainfall ranges from 750-1,150 mm, with maximum rainfall in the spring and fall. Average annual temperatures range from 17-21º C (NRCS 1997).

4.3 Estimating Curve Numbers

Daily runoff calculations for the study sites were made using the NRCS CN method, which provided a means of estimating runoff based on various land uses, soil types, and precipitation.

This calculation is based on the retention parameter, *S*, initial abstractions I_a (surface storage, interception, and infiltration prior to runoff), and the rainfall depth for the day, R_{day}, (all in mm H_20).

The retention parameter is variable due to changes in soil type, land use, and soil moisture, and is defined as (Equation 1):

$$S = 25.4\left(\frac{1000}{CN} - 10\right) \qquad (1)$$

CN varies based on one of three antecedent soil moisture conditions, CNI- dry (wilting point), CNII- average, and CNIII- wet (field capacity) (Neitsch et al. 2001). Runoff estimates would increase with increasing antecedent soil moisture condition, and thereby with increasing CN. Therefore, CNI would produce the least runoff, whereas CNIII would produce the most.

CNII was assigned based on the dominant land use and soil hydrologic group according to the SCS – Texas Engineering Technical Note No. 210-18-TX5 (1990), as shown in Table 4.2. CNI and CNIII were calculated from CNII and are defined by Equations (2) and (3) respectively (Neitsch et al. 2001). A GIS layer in grid format was created for each watershed based on CNII values at 30 m, 100 m, 1 km, and 4 km resolutions, from which CNI and CNIII grids were calculated.

$$CNI = CNII - \frac{20 \cdot (100 - CNII)}{(100 - CNII + \exp[2.533 - 0.0636 \cdot (100 - CNII)])} \tag{2}$$

$$CNIII = CNII \cdot \exp[0.00673 \cdot (100 - CNII)] \tag{3}$$

With the use of ESRI's ArcGIS 8.x software Zonal Statistics grid function, the number of pixels of the various CN values was identified within each watershed boundary at each resolution. This information was then processed to determine the weighted average CNII value for the entire watershed. Because CNs I and III are calculated from CNII, the weighted average value was not calculated for these grids. This information was used to determine the amount of spatial variability and possible error that could be caused by the use of input grids at various resolutions.

4.4 Comparing Raingauge and NEXRAD Rainfall Data

The raingauge and NEXRAD radar rainfall data was compared on a point by point basis for all watersheds to determine the accuracy of the NEXRAD rainfall data as compared with the available raingauge rainfall data. A standard statistical comparison was used to evaluate the accuracy of the NEXRAD estimates based on available raingauge data.

These statistics included estimation efficiency (Nash and Sutcliffe 1970) and standard linear regression analysis.

Table 4.2. Average curve number assignment for NLCD data.

NLCD Code	Land Use/ Land Cover	NRCS – Texas Description	CNII			
			A	**B**	**C**	**D**
11	Open water		0	0	0	0
21	low intensity residential	1/2 acre – 25% average impervious surface	54	70	80	85
22	high intensity residential	1/8 acre residential – 65% average impervious surface	77	85	90	92
23	commercial/industrial /transportation	paved streets and roads	83	89	92	93
31	bare rock/sand/clay	fallow/bare soil	77	86	91	94
32	quarries/strip mines/gravel pits	newly graded areas	77	86	91	94
33	transitional	newly graded areas	77	86	91	94
41	deciduous forest	woods – fair	36	60	73	79
42	evergreen forest	woods – fair	36	60	73	79
43	mixed forest	woods – fair	36	60	73	79
51	shrubland	brush – fair	35	56	70	77
61	orchards/vineyards/ other	woods – grass combination – fair	32	58	72	79
71	grasslands/ herbaceous	meadow	30	58	71	78
81	pasture/hay	pasture/grassland/ range – fair	49	69	79	84
82	row crops	straight row crops – good	67	78	85	89
83	small grains	straight small grains – good	67	78	85	89
84	fallow	crop residue cover – poor	76	85	90	93
85	urban/ recreational grasses	open spaces – fair	49	69	79	84
91	woody wetlands		0	0	0	0
92	emergent herbaceous wetlands		0	0	0	0

4.4.1 Estimation Efficiency. Estimation efficiency is commonly used in hydrologic model evaluation and is calculated as (Equation 4):

$$COE = 1.0 - \left(\frac{\sum_{i=1}^{n} (O_i - R_i)^2}{\sum_{i=1}^{n} (O_i - O_m)^2} \right) \tag{4}$$

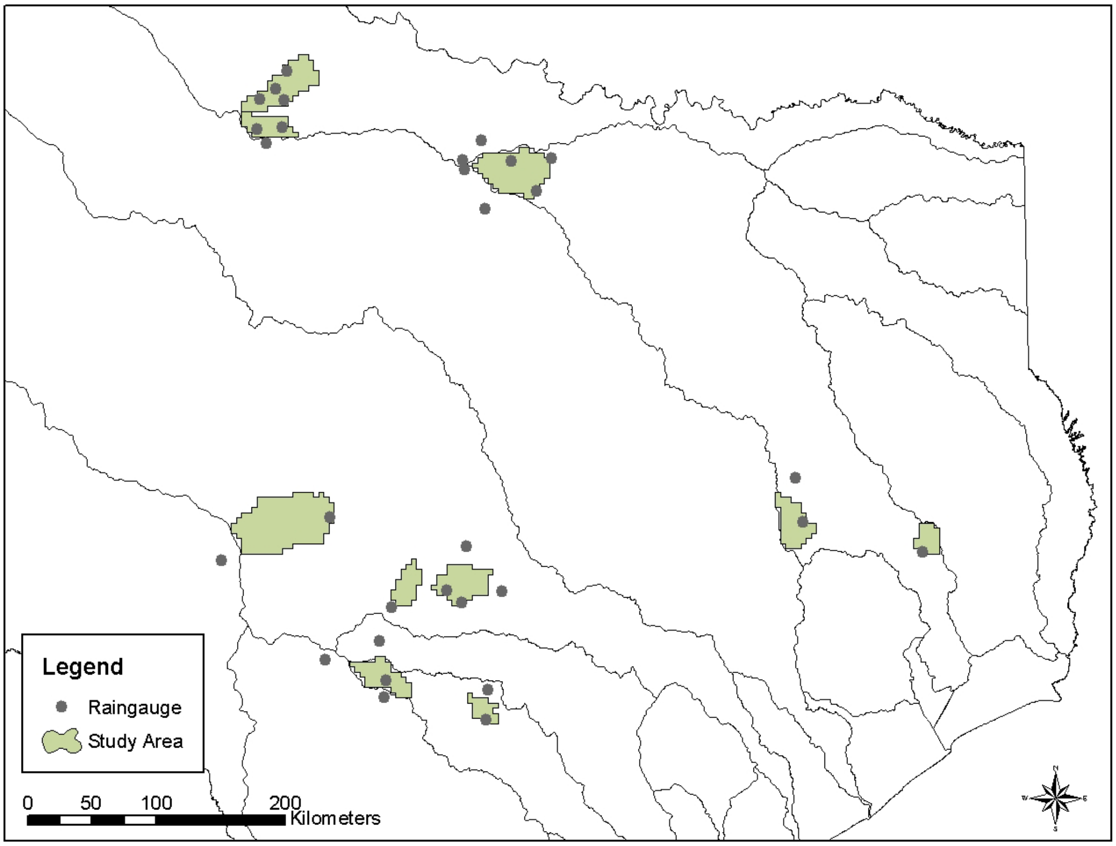
where *COE* is the coefficient of efficiency, or runoff estimation efficiency, *n* is the number of days of comparison, O_i is the observed streamgauge runoff for a watershed for day *i*, O_m is the mean observed streamgauge runoff for a watershed over all days, and R_i is the estimated runoff for a watershed for day *i*. When $R_i = O_i$, $COE = 1$. This would represent a good comparison between observed and estimated runoff values. Where $COE < 1$, the estimated runoff value is less representative than the mean value for the dataset. For this study, values greater than 0.4 are considered to be highly significant.

4.4.2 Linear Regression. For linear regression, both the coefficient of determination (r^2) and slope with intercept = 0 for the linear regression fit between observed (raingauge) and estimated (NEXRAD) rainfall values were used to determine significance.

Data was compared for all raingauge stations used in the modeling process (Figure 4.7). However, this data was compared only to the data for the NEXRAD grid in which the gauge was physically located. This helped to prevent errors based on the interpolation of rainfall amounts by NEXRAD stations between the raingauges.

First, daily data was visually inspected for shifts in rainfall records. These shifts can be caused by the time of day that data is recorded. Raingauge data is recorded at variable times, whereas hourly NEXRAD rainfall is added from 7 AM one day to 7 AM the following day to arrive at daily NEXRAD rainfall data.

Figure 4.7. NWS raingauge station locations.



All rainfall events greater than 25.4 mm were highlighted for both datasets. If these days did not match, and shifts were common throughout the datasets, the data for the raingauge was shifted up or down to match NEXRAD. Once these modifications were completed, any missing data was removed before comparison. Days with missing data in either dataset were removed from both datasets to provide more accurate day to day comparisons.

4.5 Calculating Surface Runoff

For the runoff calculation, initial abstractions (I_a) are generally approximated as 0.2 S. However, Ponce and Hawkins (1996) suggest that this may not be the most appropriate number for I_a, and that it should be interpreted as a regional parameter. To test this, 0.2 S, 0.1 S, and 0.05 S were used in the runoff equation to determine the most appropriate constant for I_a in various agro-climatic regions.

Rainfall depth for this study was obtained from corrected Stage III NEXRAD data for 1999 – 2001. Historical raingauge data was also used for validation purposes in a sample data set in the Trinity River Basin. The basic equation becomes (Equation 5):

$$Q_{surf} = \frac{\left(R_{day} - 0.2S\right)^2}{\left(R_{day} + 0.8S\right)} \qquad (5)$$

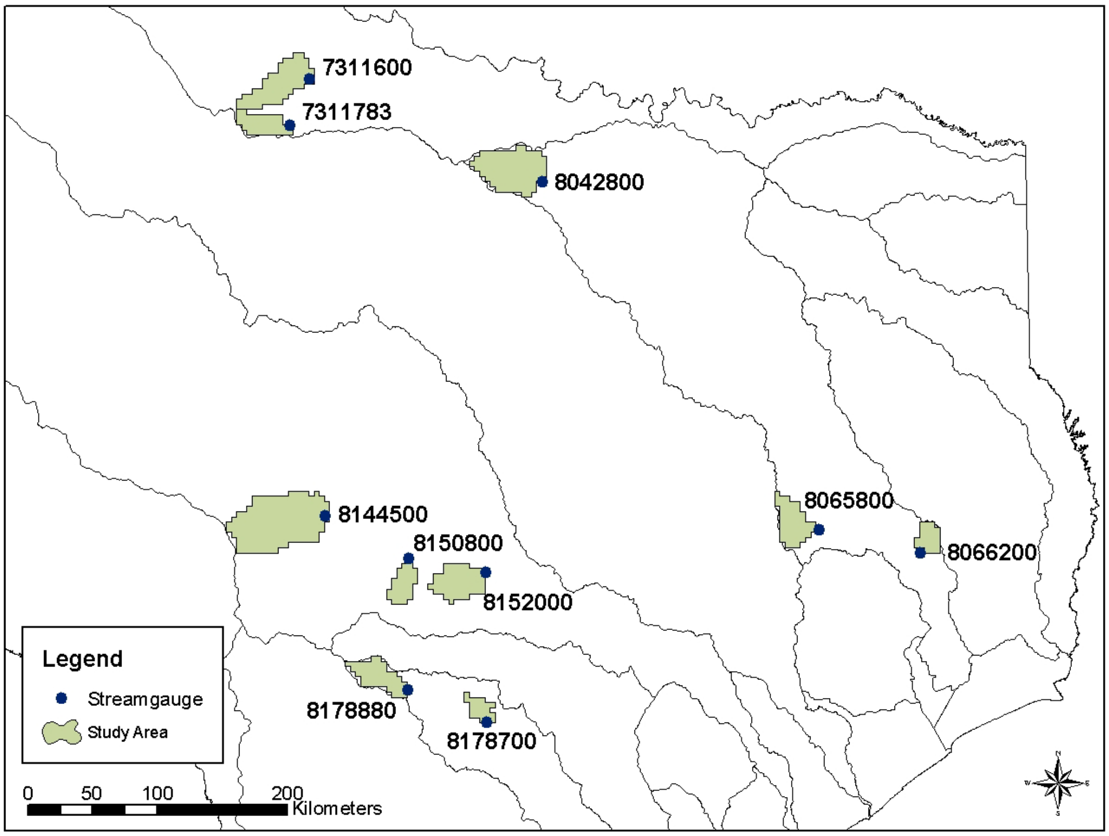
Where Q_{surf} is surface runoff in mm and R_{day} is rainfall depth for the day, also in mm. Runoff will occur only when $R_{day} > I_a$ (Neitsch et al. 2001).

A CN grid was created from the land use and soil data, and a daily rainfall grid was generated for each year within each watershed. These datasets were used as the inputs to the CN equation and processed with ESRI's ArcInfo software, and an Arc Macro Language (AML) program. This helped to speed the processing of large datasets and prevent errors that could have resulted from manual processing. The result was an estimate of runoff for each 4 km x 4 km subbasin. According to Van Mullem et al. (2002), the NRCS CN method should be used to evaluate overall watershed characteristics; therefore, the subbasin data was summarized to estimate runoff for each watershed.

4.6 Comparing Flow Data

Once data for each variation of the runoff equation was generated, the results were compared to the baseflow filtered USGS observed gauge flow data (Figure 4.8) and analyzed to determine the most appropriate method for estimating runoff in various agro-climatic regions.

Figure 4.8. USGS streamgauge station locations.



A standard statistical comparison, similar to that used in the raingauge and NEXRAD comparison, was used to evaluate the accuracy of the runoff estimates generated in this study. These statistics again included estimation efficiency and standard linear regression analysis, as well as basic summary statistics.

This was not a daily comparison, rather a comparison of runoff events generated by rainfall greater than 12 mm for both raingauge and NEXRAD rainfall data. Events with rainfall less than 12 mm produced minimal amounts of runoff and were therefore omitted from further analysis. Once an event was identified based on the amount of rainfall associated with it, the ratio of filtered streamflow to rainfall was considered. In situations where this ratio was extremely high, it was assumed that there was some sort of storm water or other point source discharge to the stream channel affecting the flow rates based on the TCEQ point source permitting system database. Therefore, these events were omitted from the comparison.

If an event was identified to have sufficient rainfall and a reasonable streamflow to rainfall ratio based on average runoff for a particular area, the rainfall, streamflow, and runoff estimates for each variation of the runoff equation were totaled for that event. The event would begin on the first day of significant rainfall, and continue until the streamflow had returned to normal levels, similar to the levels before the rainfall event began.

Statistical comparisons were then completed for the summarized events. In addition, the data was separated into three seasonal categories for further comparison. These seasons generally mimic the pre, growing, and post season vegetation changes, and ran from January 1st to April 25th, April 26th to September 30th, and October 1st to December 31st. The same statistical comparison that was used for the entire dataset was then repeated for each season. These comparisons were completed for each watershed individually.

Next, all events from all watersheds were ranked by rainfall in natural pairs for each river basin. They were then separated into the top 20%, middle 60%, and lower 20% of rainfall events for a ranked pair comparison. Estimation efficiency and regression analysis were performed on each of these categories to determine the accuracy of predictions with varying rainfall. This process was then repeated for all identified events for all basins in this study and statistics were generated for a combined ranked pair analysis.

The Trinity River Basin watersheds were used to evaluate the effectiveness of the runoff equation variations, as well as raingauge and NEXRAD rainfall data in the modeling processes used in this study. Based on this information, only the more effective methods were used in the remaining watersheds.

V. RESULTS AND DISCUSSION

5.1 Evaluation of Spatial Variability in Curve Number Assignment

To determine the amount of spatial variability and possible error that could be caused by the use of input grids at various resolutions, the weighted average CN for each watershed was calculated from 30 m, 100 m, 1 km, and 4 km using CNII grids (Table 5.1).

Table 5.1. Weighted average CN by watershed.

Watershed	30 m	100 m	1 km	4 km
Trinity-1	53	53	53	51
Trinity-2	58	58	59	57
Trinity-3	58	58	58	60
Red-1	51	51	51	51
Red-2	50	50	50	49
LCR-1	57	57	57	57
LCR-2	59	59	59	59
LCR-3	55	55	55	54
SA-1	58	58	58	57
SA-2	65	65	66	63

The most overall change between values among various grids was found in the Trinity River Basin. Values ranged from 51 to 53 in Trinity-1, 57 to 59 in Trinity-2, and 58 to 60 in Trinity-3. In the Red River Basin, Red-1 showed no difference in weighted CN value between the various resolutions. However, Red-2 values ranged from 49 to 50. For the Lower Colorado River Basin, the only difference in CN values was found in LCR-3, with a range of 54 to 55. All other basins had the same CN value at all resolutions. Finally, in the San Antonio Basin, for SA-1 values ranged from 57 to 58. However, in the SA-2 watershed, the values ranged from 63 at the 4 km resolution, to 65 at the 30 m and 100 m resolutions, and the 66 at the 1 km resolution. In general, these changes are negligible and the findings are not surprising due to the fact that the selected watersheds had a mostly homogenous land use distribution and a regionally generalized soils dataset was used for this study.

Hence, the evaluation of various runoff models was not completed for each resolution based on the small variability in weighted average CN values within each watershed. It was determined that running the models with grids at various resolutions would cause little change in the runoff estimates. Therefore, only the 4 km CN grid was used throughout the study.

5.2 Comparison of Raingauge and NEXRAD Rainfall Data

According to Jayakrishnan (2001), NEXRAD rainfall estimates have improved since 1999. In order to test this, a statistical comparison of raingauge and NEXRAD rainfall data was completed.

Many of the raingauge stations used in this study were missing at least one day of rainfall data. In one instance a single gauge was missing 746 days. In addition, many raingauge stations are no longer active, or have moved. In four of the study watersheds, only one gauge remains active. Generally, this data is collected on a cooperative basis and in most cases, study sites are in rural areas. The quality of this data and its processing are therefore not strictly maintained. None of the NEXRAD radar stations were missing rainfall data for the study period. Therefore, in cases where there were observed data shifts, raingauge data was shifted up or down to match the NEXRAD rainfall. In general, the raingauge and NEXRAD rainfall measurements matched reasonably well in areas where there was a complete data record.

The similarity between these two datasets was based on coefficient of efficiency (*COE*) and regression analysis. A *COE* = 1 would represent a good match between the estimated (NEXRAD) and observed (raingauge) rainfall measurements. Additionally, for the regression analysis, a slope = 1 (with y-intercept = 0) and coefficient of determination (r^2) = 1 would also represent a good match between estimated and observed rainfall measurements and support the use of NEXRAD rainfall data for use in the CN method runoff equation.

5.2.1 Trinity River Basin. There are seven raingauge stations in the Trinity-1 watershed; however, there are only two stations in Trinity-2, and one station in Trinity-3.

Five of the seven stations in Trinity-1 show an excellent match between the two datasets, one is fair, and one is rather poor (Appendix A, Table A-1). Station 1 has a *COE* of 0.60, a slope of 0.82, and an r^2 value of 0.64. Station 2 has a *COE* of 0.56, a slope of 0.74, and an r^2 of 0.59. Station 3 is the best overall match between the datasets with a *COE* of 0.79, and a slope of 0.84 with an r^2 of 0.79 (Figure 5.1). Station 5 had a *COE* of 0.60, a slope of 0.72, and an r^2 of 0.61. Finally, station 7 was again a very close match, only station 3 was a better match. This station had a *COE* of 0.74, a slope of 0.81, and an r^2 value of 0.74.

Station 4 was a fairly decent match, and considered to be statistically significant. The *COE* for this comparison was 0.41, the slope was 0.59, and the r^2 was 0.44. Station 6, on the other hand, showed a poor comparison between the datasets. The *COE* for this station was 0.03, the slope was 0.50, and the r^2 was 0.23 (Figure 5.2). Station 6 was missing a total of 67 days of data that were removed from both datasets. However, the rainfall for the missing days seems to have been recorded on a single day when recording resumed. The totals for that day match the NEXRAD rainfall estimates corresponding to all of the missing days.

Figure 5.1. Trinity-1 station 3 raingauge and NEXRAD comparison.

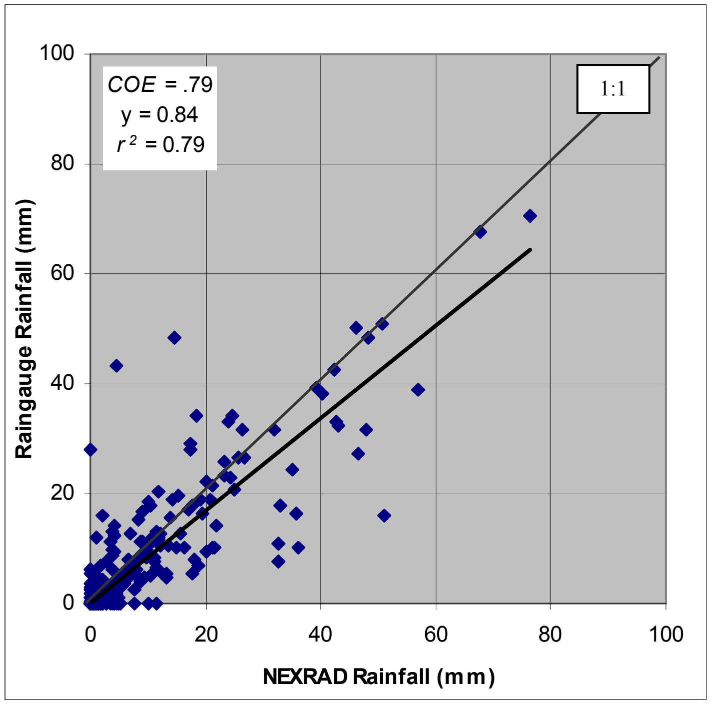
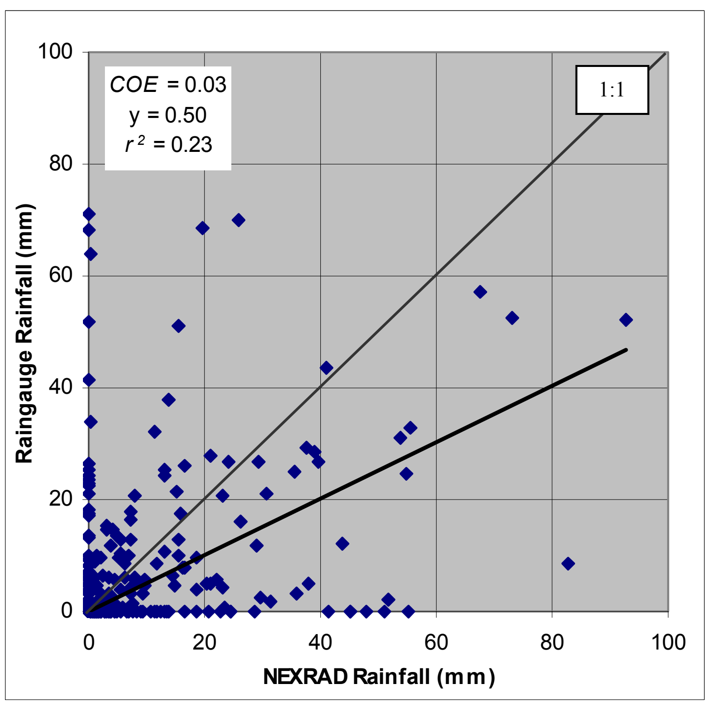


Figure 5.2. Trinity-1 station 6 raingauge and NEXRAD comparison.



The rainfall estimates from NEXRAD stations in Trinity-2 (Appendix A, Table A-2) and Trinity-3 (Appendix A, Table A-3) matched the raingauge rainfall data reasonably well. In Trinity-2, station 1 had a *COE* of 0.37, a slope of 1.06, and an r^2 of 0.63. Station 2 had a *COE* of 0.61, a slope of 0.95, and an r^2 of 0.69 (Figure 5.3). In the Trinity-3 watershed, there was only one station comparison. Data was unavailable for all other stations in this watershed. For the available station the *COE* was 0.69, the slope was 0.90, and the r^2 value was 0.72 (Figure 5.4). These findings, in general, help to establish the fact that the level of accuracy of NEXRAD can be reasonably well established and that the data is appropriate for this study.

Figure 5.3. Trinity-2 station 2 raingauge and NEXRAD comparison.

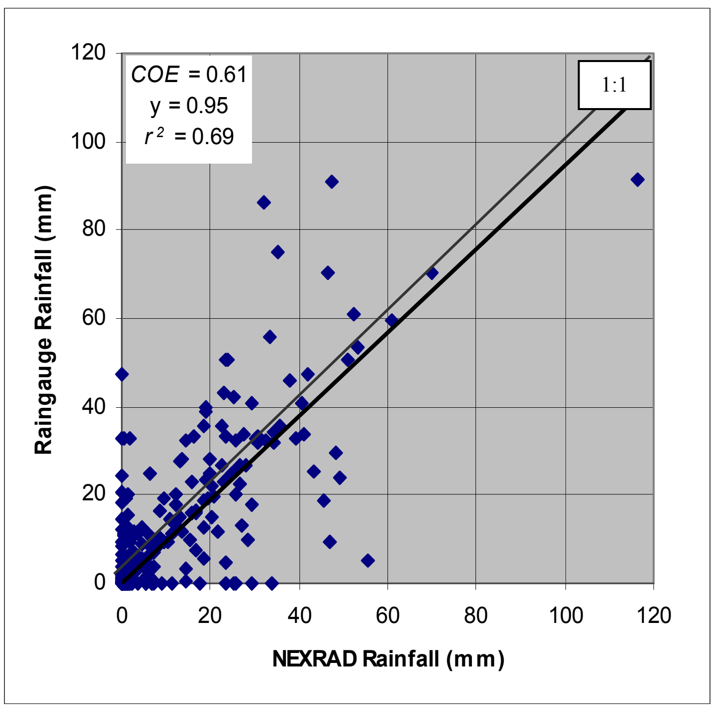
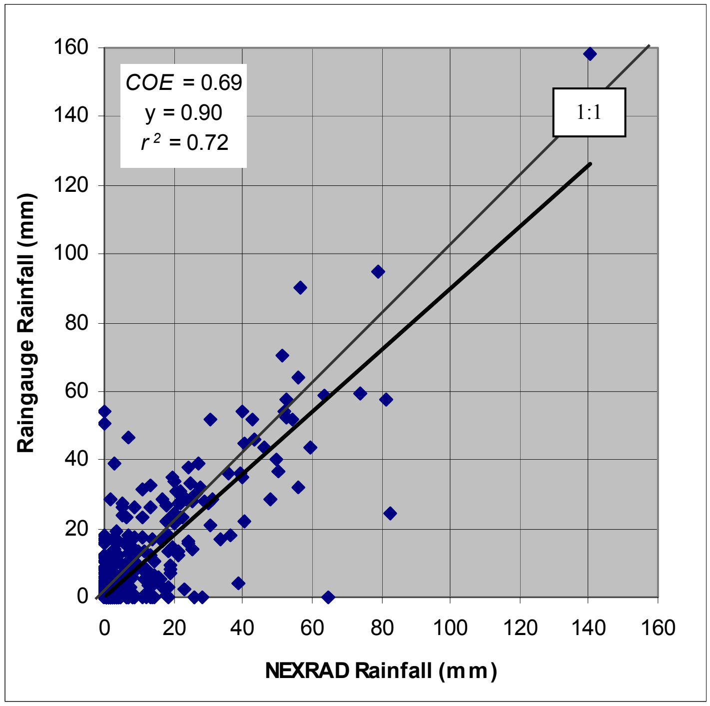


Figure 5.4. Trinity-3 station 1 raingauge and NEXRAD comparison.

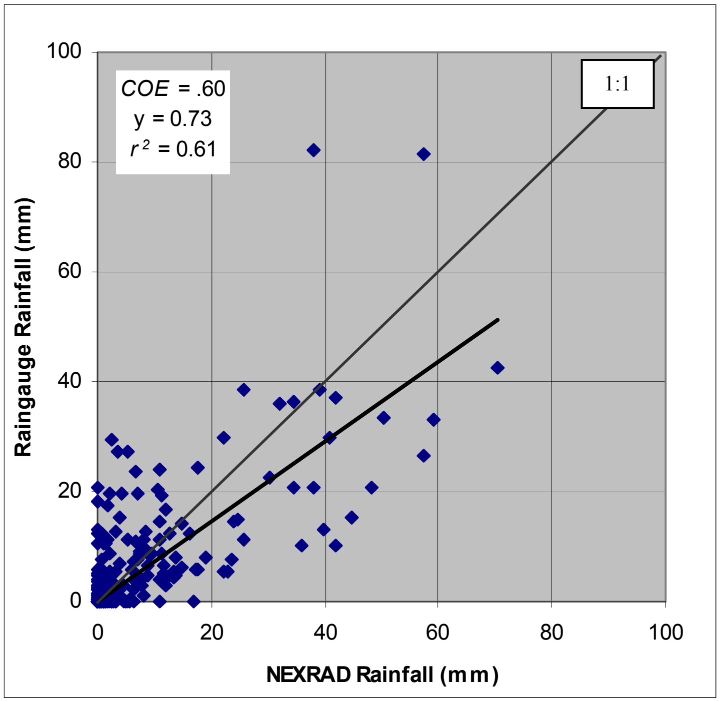


5.2.2 Red River Basin. There are four raingauge stations in the Red-1 watershed, and three stations in Red-2.

Red-1 showed a very high correlation between the rainfall recorded by the raingauge and NEXRAD stations (Appendix A, Table A-4), despite the large number of missing days of data (640 days for one station and 121 for another, out of 1,096 days total for each station). These days were removed from the two datasets before comparison.

In the Red-1 watershed, station 1 had a high *COE* value (0.59); however, this station has the lowest slope and r^2 values, both were 0.59. Station 2 had the highest overall *COE* value and regression statistics of all of the stations in this watershed, with a *COE* of 0.60, a slope of 0.73, and an r^2 value of 0.61 (Figure 5.5). Station 3 has the lowest *COE* value at 0.44. The slope and r^2 for this station were 0.76 and 0.53. Finally, station 4 had a *COE* of 0.57, a slope of 0.68, and an r^2 value of 0.58.

Figure 5.5. Red-1 station 2 raingauge and NEXRAD comparison.



Whereas Red-1 showed a very high match between the raingauge and NEXRAD rainfall data, Red-2 did not (Appendix A, Table A-5). Station 1 had a *COE* of -0.38, a slope of 0.51, and an r^2 of 0.17. In addition, there were 28 events that with a greater than 25.4 mm difference in the measured rainfall for that day. Station 2 showed a somewhat better match between the two datasets. The *COE* for this station was 0.34, the slope was 0.68, and the r^2 was 0.44. This station was missing 62 days of data and had 12 days with a greater than 25.4 mm difference in recorded daily rainfall. The final station in this watershed, station 3, had a *COE* of 0.38, a slope of 0.65, and an r^2 value of 0.44. This station was missing a total of 455 days of rainfall data, including all of 1999.

5.2.3 Lower Colorado River Basin. There are two raingauge stations in the LCR-1 and LCR-2 watersheds and four in LCR-3.

The two LCR-1 stations both showed a poor match between raingauge and NEXRAD rainfall data (Appendix A, Table A-6). Station 1 had a *COE* of 0.08, a slope of 0.65, and an r^2 of 0.33 (Figure 5.6). Station 2 has a *COE* value of -0.01, a slope of 0.56, and an r^2 of 0.26 (Figure 5.7). In this watershed there were several inactive stations that had to be removed from comparison, as well as missing days, and some inconsistent shifts in rainfall events. This inconsistency prevented adjusting the entire dataset.

Figure 5.6. LCR-1 station 1 raingauge and NEXRAD comparison.

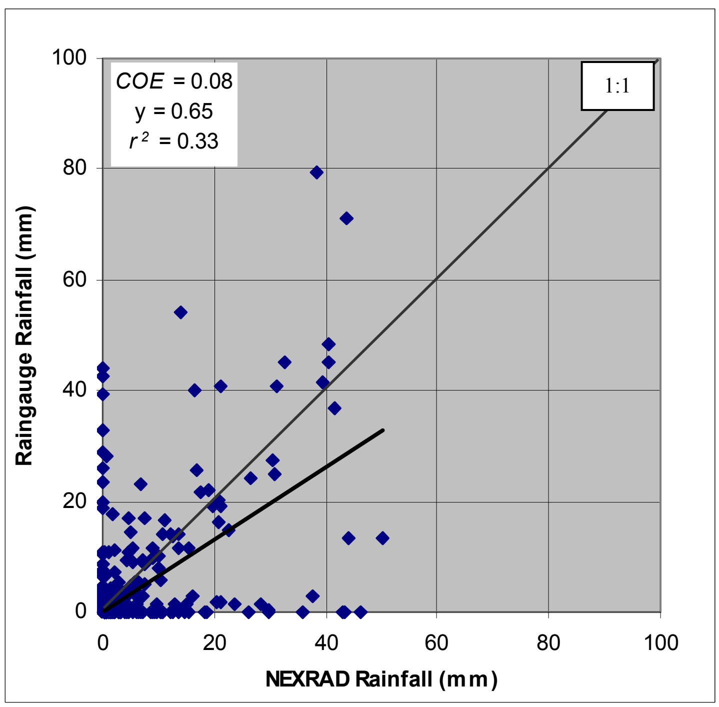
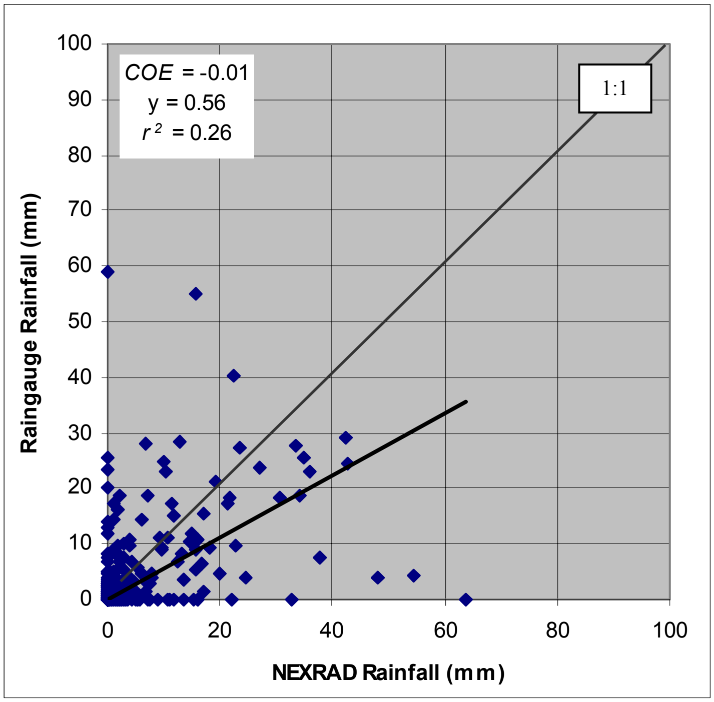


Figure 5.7. LCR-1 station 2 raingauge and NEXRAD comparison.



In the LCR-2 watershed, both stations showed a very good match between the two datasets (Appendix A, Table A-7). For station 1, the *COE* was 0.72, the slope was 0.84, and the r^2 was 0.73. Station 2 was an even better match, with a *COE* of 0.73, a slope of 0.98, and an r^2 value of 0.78 (Figure 5.8).

Three of the four stations in LCR-3 were equally well matched (Appendix A, Table A-8). Station 1 had a *COE* of 0.76, a slope of 0.84, and an r^2 of 0.76. Station 2 had a *COE* of 0.72, a slope of 0.96, and an r^2 of 0.76. Station 3 had a *COE* of 0.73, a slope of 0.98, and an r^2 of 0.78 (Figure 5.9). Station 4 was the poorest match in this watershed with a *COE* of 0.56, a slope of 0.87, and an r^2 of 0.63, which is still a very good overall match.

Figure 5.8. LCR-2 station 2 raingauge and NEXRAD comparison.

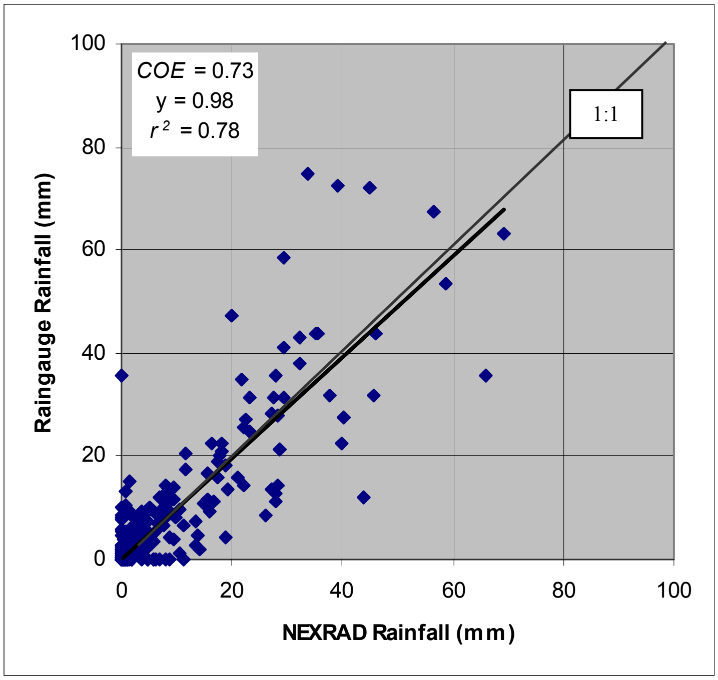
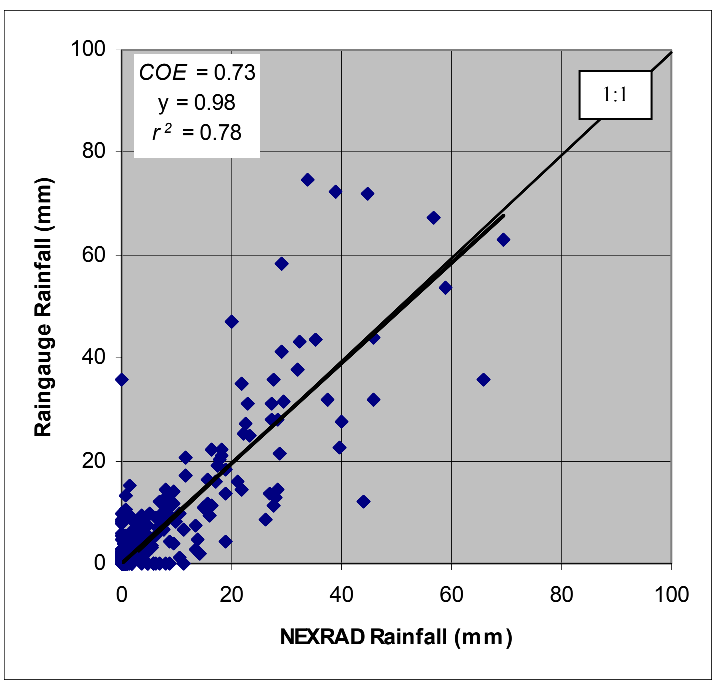


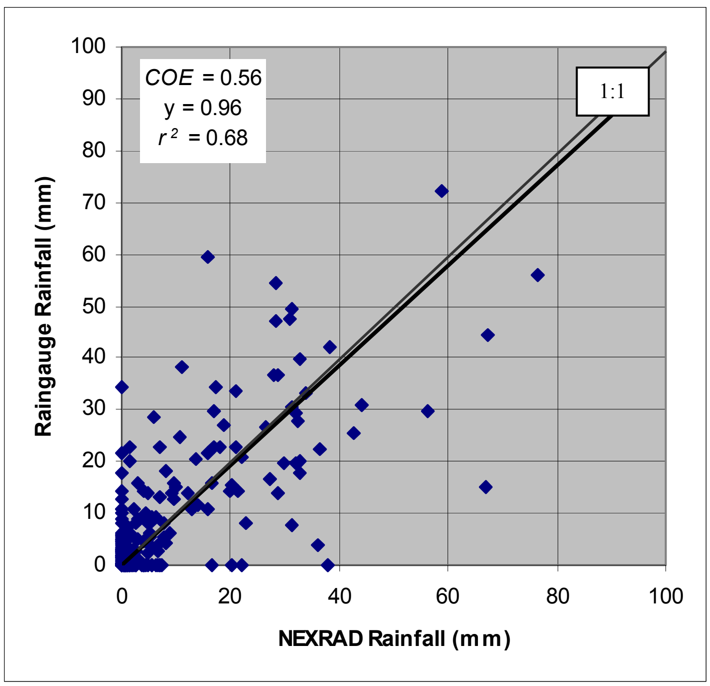
Figure 5.9. LCR-3 station 3 raingauge and NEXRAD comparison.



5.2.4 San Antonio River Basin. There are four raingauge stations in the SA-1 watershed and two in SA-2.

The stations in SA-1 generally show a good match between the raingauge and NEXRAD rainfall data (Appendix A, Table A-9). Station 1 had a *COE* of 0.56, a slope of 0.96, and an r^2 of 0.68 (Figure 5.10). Station 2 had the lowest *COE* value, at 0.31, and a slope of 1.02 with an r^2 of 0.60. Station 3 had a *COE* of 0.65, a slope of 0.82, and an r^2 of 0.68. Finally, station 4 had a *COE* of 0.54, with a slope of 0.89, and an r^2 of 0.63.

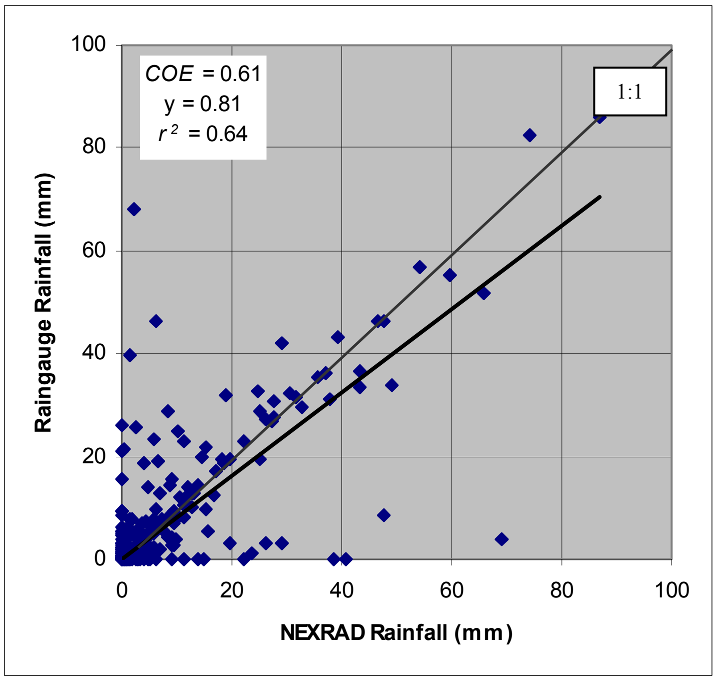
Figure 5.10. SA-1 station 1 raingauge and NEXRAD comparison.



For SA-2, station 1 showed the worst match between the two datasets (Appendix A, Table A-10). The *COE* for this station was 0.27, the slope was 0.81, and the r^2 value was 0.47. A breakdown of the data by year shows there was a good match for the years

1999 and 2001. For 1999, the *COE* was 0.48, with a slope of 0.87, and an r^2 of 0.60. For 2001, the *COE* was 0.52, slope was 0.87, and the r^2 was 0.61. However, for the year 2000, the *COE* was -0.24, the slope was 0.68, and the r^2 was 0.26. In this watershed, station 2 had a *COE* of 0.61, a slope of 0.81, and an r^2 value of 0.64 (Figure 5.11).

Figure 5.11. SA-2 station 2 raingauge and NEXRAD comparison.



Missing raingauge data, data shifts, and inactive or moved gauges, along with the inherent human error associated with these gauges makes them somewhat less reliable than the NEXRAD radar rainfall data. In general, in cases where there were complete datasets for both raingauge and NEXRAD, NEXRAD compared quite well with the raingauge data. This, in addition to the fact that the NEXRAD data is complete and available daily, makes it a more useful dataset for this type of modeling research. However, based on some of the evidence here, it appears that there is still a need to verify accurate calibration of the NEXRAD data before using it in modeling applications. This could be achieved through post calibration of NEXRAD stage III data using some of the real-time raingauge data obtained from airport network stations. Using this information, a bias correction factor could be estimated and extended to the entire study area with the proper statistical method. Runoff could then be recomputed with improved accuracy.

5.3 Evaluation of NRCS Curve Number Method Alternatives for Various Agro-climatic Regions from 1999 – 2001

For this analysis, CNI and CNII were used as the CN variables in the runoff equation with an I_a ratio of 0.1, 0.2, and 0.05. Also, raingauge and NEXRAD data were each used as the rainfall input for the runoff equation and the results of each of the alternatives was then evaluated with observed runoff to determine which would produce the most statistically significant results.

Estimation efficiency and linear regression analysis were completed for each watershed to determine the significance of the runoff estimates. Again, a *COE*, slope, and r^2 equal to one would represent a best match between estimated and observed runoff values. Also, these comparisons are based on summarized events with rainfall greater than 12 mm.

5.3.1 Trinity River Basin. The watersheds in this basin were used to evaluate variations of the NRCS CN method for estimating runoff before application in other watersheds. Only the most effective methods were used in the remaining study areas.

The runoff equation was first run with CNI and CNII, using 0.2, 0.1, and 0.05 for the I_a ratio. Through a systematic procedure as explained in the materials and methods section, events were isolated from the three year daily model run. Trinity-1 had a total of 31 identified events (Appendix B, Table B-1) for both the CNI and CNII alternatives (Table 5.2). For CNI, with 0.2 as the I_a ratio, the *COE* was -0.02, whereas the *COE* with 0.1 was 0.54. The *COE* with 0.05 was -0.29. In addition, the slope and r^2 for the CNI – 0.1 alternative was 0.95 and 0.53, respectively (Figure 5.12). This alternative appeared to be the best match for modeled and observed runoff in this watershed for the events during this study period.

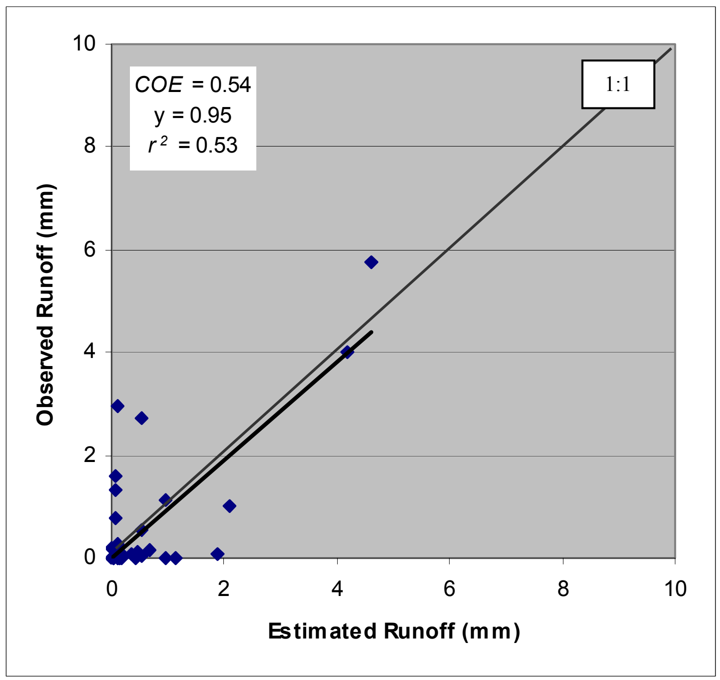
For CNII, none of the alternatives used in this study were representative of the observed runoff in this watershed. The alternative that most closely matched observed runoff was the CNII – 0.2 alternative. The *COE* was -1.57, slope was 0.38, and the r^2 was 0.44. This is to be expected with the close match in the CNI – 0.1 alternative. Using CNII would suggest a wetter antecedent soil moisture and thereby increase the runoff associated with an event. This alternative was more representative than the 0.1 and 0.05 alternatives because using 0.2 for the I_a ratio would reduce some of the runoff by increasing the total initial abstractions, thereby preventing more of the runoff from reaching the stream channel.

Next, based on information from Ponce and Hawkins (1996), 0.05 was used for the I_a ratio, with a modified CN that was back calculated using the retention parameter (*S*) equation. This new CN was used in the runoff equation with the 0.05 I_a value. For this alternative, 30 events were identified. Again, this process did not produce a representative match to the observed runoff. The *COE* for this alternative was -2.73, the slope was 0.33, and the r^2 value was 0.44.

Table 5.2. Summary of NRCS CN method alternatives for the Trinity-1 watershed.

Rainfall Data	Curve Number	Identified Events	0.2 I_a Coefficient			0.1 I_a Coefficient			0.05 I_a Coefficient		
			COE	Slope	r^2	COE	Slope	r^2	COE	Slope	r^2
NEXRAD	CNI	31	-0.02	4.30	0.33	0.54	0.95	0.53	-0.29	0.50	0.56
NEXRAD	CNII	31	-1.57	0.38	0.44	-8.07	0.23	0.46	-15.40	0.18	0.46
Raingauge	CNI	20	-	-	-	0.09	0.62	0.43	-	-	-

Figure 5.12. Trinity-1 NRCS CNI – 0.1 alternative.



For the Trinity-2 watershed, again the CNI and CNII alternatives with 0.2, 0.1, and 0.05 I_a ratios were used (Table 5.3). For the CNI alternative, 32 events were identified (Appendix B, Table B-2). The *COE* for the 0.2 alternative was 0.77, with a slope of 1.61, and an r^2 of 0.91. For the 0.1 alternative, the *COE* was 0.90, slope was 0.85, and the r^2 was 0.93 (Figure 5.13). The 0.05 alternative had a *COE* of 0.53, a slope of 0.62, and an r^2 of 0.92. Again, the CNI – 0.1 alternative appears to produce overall results that are the most comparable to the observed runoff.

For the CNII alternative, again, no results were considered to be significant enough for this study. The alternative that produced results that most closely matched observed runoff was the CNII – 0.2 alternative, with a *COE* of -6.07, a slope of 0.28, and an r^2 of 0.91. The runoff was also estimated for the 0.05 alternative with the back-calculated CN. The *COE* was -789.11, with a slope of 0.32, and an r^2 of 0.28.

Finally, the raingauge rainfall data was used with the CNI – 0.1 variation of the runoff equation. For this alternative, 38 events were identified, with a *COE* of -1.38, a slope of 0.38, and an r^2 of 0.23.

For Trinity-3, CNI and CNII and the back-calculated CN with 0.05 were the only alternatives completed (Table 5.4). It was determined that the use of raingauge rainfall data did not produce reasonable results, and therefore model runs were not carried out.

For CNI, 40 events were identified (Appendix B, Table B-3). For the 0.2 alternative the *COE* was 0.78, the slope was 1.15, and the r^2 was 0.79. For the 0.1 alternative, the *COE* was 0.64, slope was 0.77, and the r^2 was 0.72 (Figure 5.14). For the 0.05 alternative, the *COE* was 0.31, with a slope of 0.61, and an r^2 of 0.66. Again, the CNI – 0.1 alternative was determined to produce the best overall match between estimated and observed runoff.

Table 5.3. Summary of NRCS CN method alternatives for the Trinity-2 watershed.

Rainfall Data	Curve Number	Identified Events	0.2 I_a Coefficient			0.1 I_a Coefficient			0.05 I_a Coefficient		
			COE	Slope	r^2	COE	Slope	r^2	COE	Slope	r^2
NEXRAD	CNI	32	0.77	1.61	0.91	0.90	0.85	0.93	0.53	0.62	0.92
NEXRAD	CNII	32	-6.07	0.28	0.91	-9.82	0.23	0.89	-12.38	0.21	0.88
Raingauge	CNI	38	-	-	-	-1.38	0.38	0.23	-	-	-

Figure 5.13. Trinity-2 NRCS CNI – 0.1 alternative.

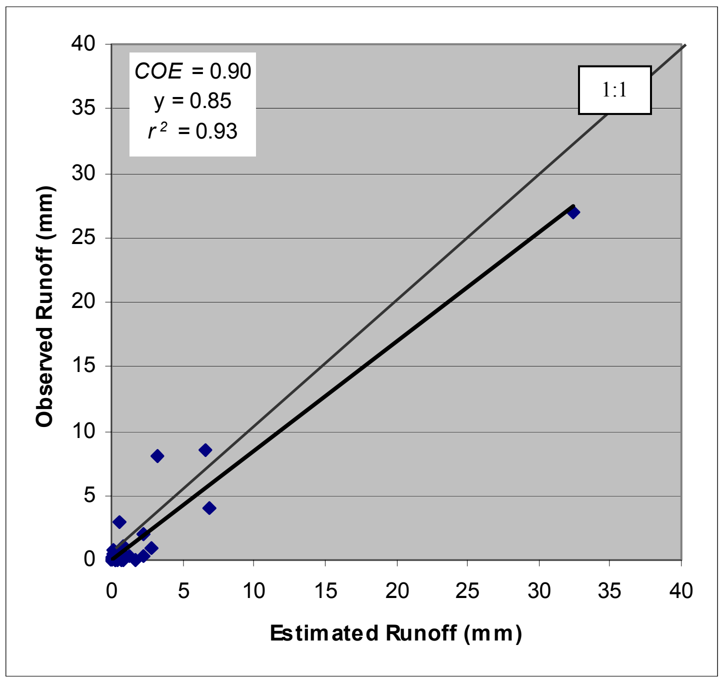
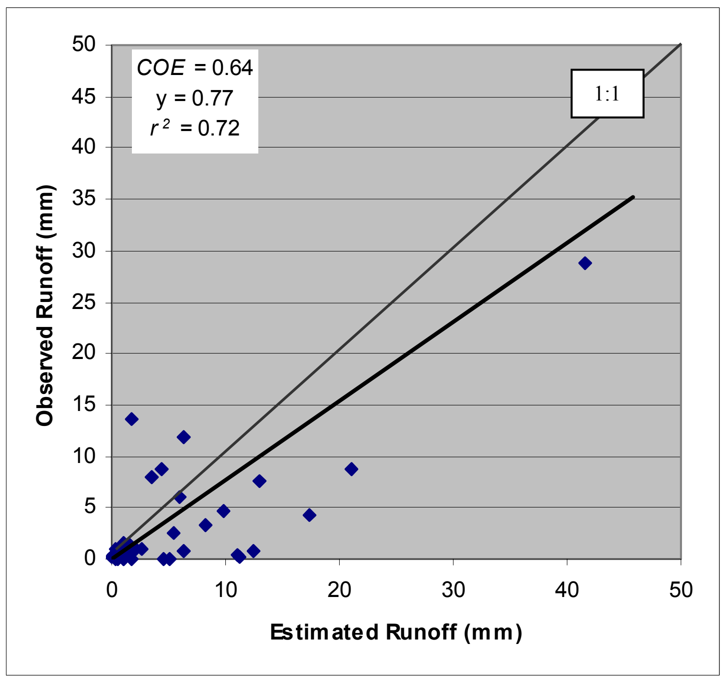


Table 5.4. Summary of NRCS CN method alternatives for the Trinity-3 watershed.

Rainfall Data	Curve Number	Identified Events	0.2 I_a Coefficient			0.1 I_a Coefficient			0.05 I_a Coefficient		
			COE	Slope	r^2	COE	Slope	r^2	COE	Slope	r^2
NEXRAD	CNI	40	0.78	1.15	0.79	0.64	0.77	0.72	0.31	0.61	0.66
NEXRAD	CNII	40	-1.09	0.41	0.62	-2.51	0.33	0.56	-3.61	0.29	0.53

Figure 5.14. Trinity-3 NRCS CNI – 0.1 alternative.



The statistics for all of the CNII alternatives and the back-calculated CN – 0.05 alternative showed poor results for the representation of estimated to observed runoff. Of these alternatives, the CNII – 0.2 alternative most closely matched observed runoff, with a *COE* of -1.09, a slope of 0.41, and an r^2 value of 0.62.

After comparing the results for each of the three Trinity River Basin watersheds, it was determined that using the CNI – 0.1 variation of the runoff equation, with NEXRAD radar rainfall input produced the most accurate runoff estimates when compared with filtered streamflow data. The results from this alternative were used in the seasonal and ranked pair analysis for this basin, and to model streamflow in the remaining watershed study areas. In cases where this alternative did not produce reasonable results, additional alternatives which might improve the results were run for comparative purposes.

5.3.2 Red River Basin. The CNI – 0.1 alternative was used as a first run in this basin. Additional alternatives were unnecessary based on the comparison of estimated to observed runoff in the watersheds in this basin (Table 5.5).

Table 5.5. Summary of the NRCS CNI – 0.1 alternative for the Red River Basin watersheds.

Watershed	Identified Events	COE	Slope	r^2
Red-1	22	0.97	1.10	0.98
Red-2	25	0.43	0.77	0.51

For the Red-1 watershed, 22 total events were identified for the three year study period (Appendix B, Table B-4). The *COE* for this watershed with the CNI – 0.1 alternative was 0.97, slope was 1.10, and the r^2 was 0.98 (Figure 5.15). Based on the results for this model run, it was decided that additional runs were unnecessary. The CNI – 0.1

alternative produced runoff estimates that closely matched the observed runoff obtained from the filtered streamflow data.

For Red-2, 25 events were identified (Appendix B, Table B-5). First, the CNI – 0.1 variation was used to estimate runoff. The *COE* for this run was 0.43, the slope was 0.78, and the r^2 was 0.51 (Figure 5.16). It was again determined that the CNI – 0.1 variation of the runoff equation produced the best results, and the seasonal and ranked pair analysis was completed for this alternative. However, it should be noted that the raingauge and NEXRAD point comparison for this watershed was not statistically significant. This would explain the less significant values produced by the modeling process in this watershed.

Figure 5.15. Red-1 NRCS CNI – 0.1 alternative.

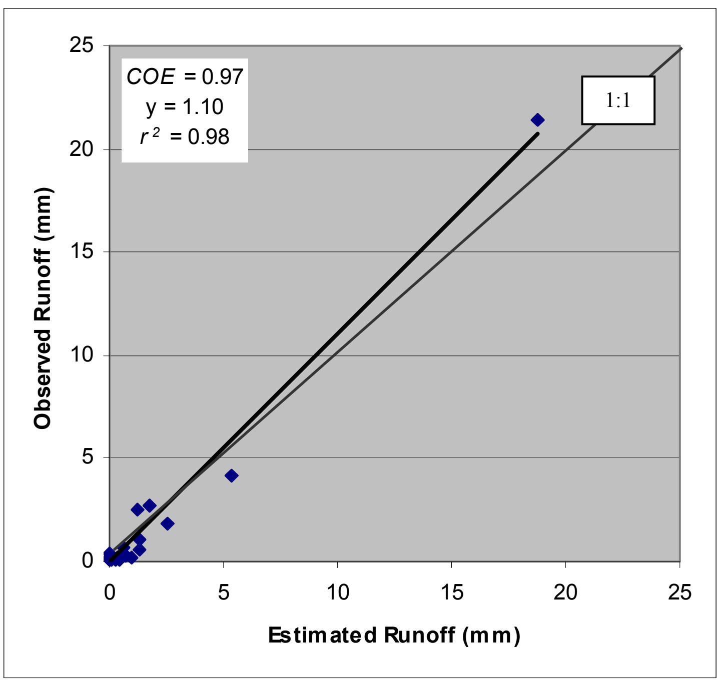
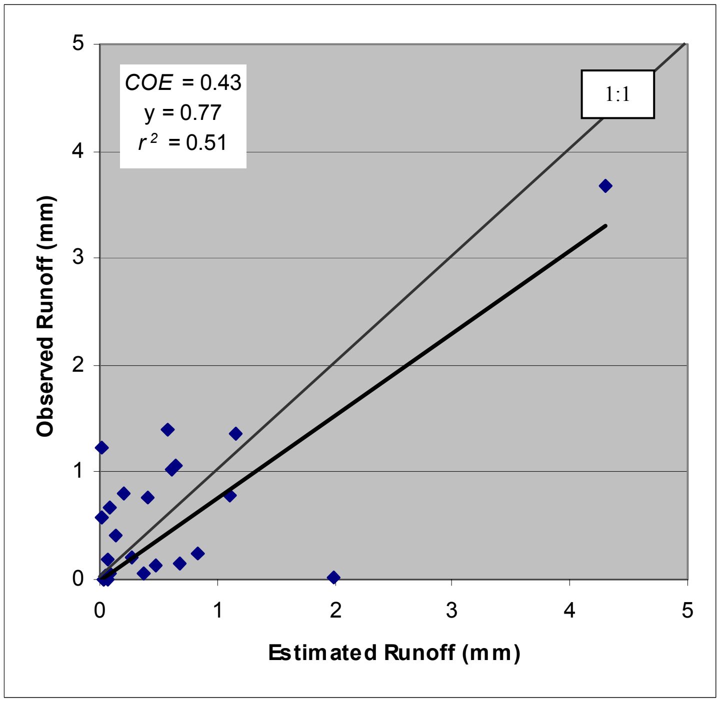


Figure 5.16. Red-2 NRCS CNI – 0.1 alternative.



5.3.3 Lower Colorado River Basin. For the three watersheds in this basin, the CNI – 0.1 alternative was used as a first run. However, because this alternative method did not produce satisfactory results for LCR-1, the CNI – 0.2 alternative was also used for comparative purposes (Table 5.6).

Table 5.6. Summary of the NRCS CNI – 0.1 and CNI – 0.2 alternatives for the Lower Colorado River Basin watersheds.

Watershed	Identified Events	0.2 I_a Coefficient			0.1 I_a Coefficient		
		COE	Slope	r^2	COE	Slope	r^2
LCR-1	38	0.02	0.74	0.09	-3.98	0.33	0.40
LCR-2	30	-	-	-	0.56	0.73	0.68
LCR-3	15	-	-	-	0.85	1.17	0.86

For LCR-1, 38 events were identified (Appendix B, Table B-6). Results from the CNI – 0.1 model run produced a *COE* of -3.98, a slope of 0.33, and an r^2 value of 0.40. After individual event comparison, an over-prediction of runoff estimates was identified. Therefore the CNI – 0.2 alternative was used for comparison purposes. This run produced a *COE* of 0.02, a slope of 0.74, and an r^2 of 0.09. An individual event comparison of the results produced by this alternative helped to identify an under-prediction of runoff estimates. The inaccuracy of these results led to further analysis to determine the cause for such results.

First, the raingauge and NEXRAD comparison in this watershed highlighted issues in the NEXRAD calibration that would prevent an accurate runoff estimate. Only two comparison points for raingauge and NEXRAD stations were identified for this watershed, and the comparison was not statistically significant at either point. This lack of adequate data prevents accurate modeling of the watershed with either rainfall data source.

Next, point source issues were investigated. There are two points that could lead to issues in modeling streamflow in this watershed that are located at the outlet of the identified watershed boundary. Although these are both considered minor facility classes by the TCEQ, they may have some affect on the actual flow in the stream channel. One is a retention pond for a feed lot facility and the other is a discharge point for the City of Menard, Texas.

Furthermore, a comparison of the NLCD dataset to the previous USGS land cover dataset from the early 1980s was inconclusive in that there was no accurate way to directly compare the datasets. The 1980 dataset is at a 250 m resolution, whereas the NLCD dataset is at a 30 m resolution. In addition, the classification schemes used for the two datasets were somewhat different. The inability to compare the datasets leads to the conclusion that possibly the area is classified incorrectly or in such a manner that would lead to an incorrect CN assignment. Also, the area was classified as shrubland in fair condition, which would indicate 50 – 75% ground cover according to the SCS (1990). Further investigation of the actual field condition could help to identify a more appropriate CN assignment.

Based on the poor results in this watershed it was eliminated from further analysis and removed from the overall comparisons within the Lower Colorado River Basin. However, this watershed is composed of approximately 71% shrubland. Therefore, it was determined that this finding should not have a major effect in other watersheds that are not predominately shrubland but have a more mixed land cover.

A total of 30 events were identified for the LCR-2 watershed (Appendix B, Table B-7). The CNI – 01 alternative produced a *COE* of 0.56, a slope of 0.73, and an r^2 of 0.68 (Figure 5.17). These results were considered acceptable, and this alternative was chosen for further analysis.

In the LCR-3 watershed, only 15 events were identified (Appendix B, Table B-8). Many events were not included because of odd runoff to rainfall ratios. The runoff from many events seemed to be “flashy”, *i.e.* rainfall generated relatively high runoff (occasionally exceeding rainfall) in a short period of time. This could be attributed to storm water or other point source discharge. For the events that were identified, the CNI – 0.1 alternative was again used. The *COE* was 0.85, slope was 1.17, and the r^2 was 0.86 (Figure 5.18). Based on the overall accuracy of the results generated by the CNI – 0.1 alternative, no other alternatives were tested in this watershed.

Figure 5.17. LCR-2 NRCS CNI – 0.1 alternative.

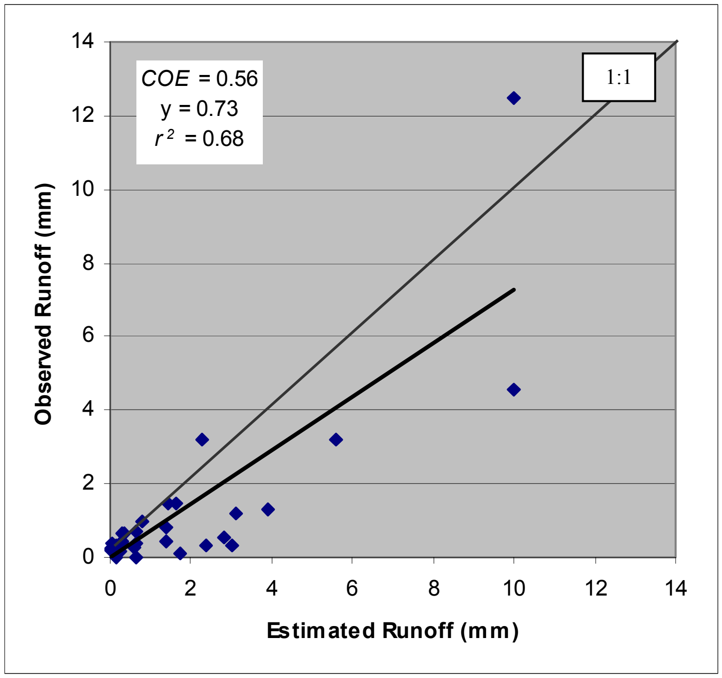
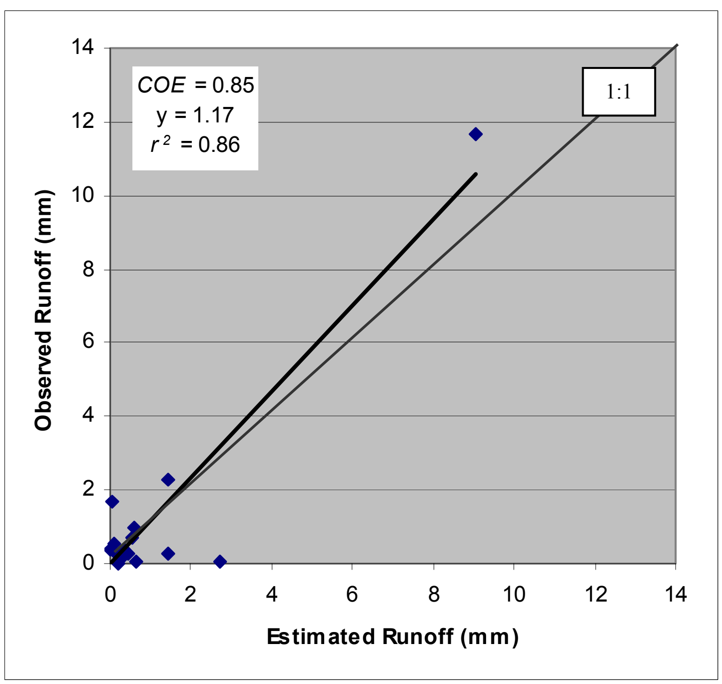


Figure 5.18. LCR-3 NRCS CNI – 0.1 alternative.



5.3.4 San Antonio River Basin. For the two watersheds in this basin, both CNI – 0.1 and CNI – 0.2 alternatives were used (Table 5.7).

Table 5.7. Summary of the NRCS CNI – 0.1 and CNI – 0.2 alternatives for the San Antonio River Basin watersheds.

Watershed	Identified Events	0.2 I_a Coefficient			0.1 I_a Coefficient		
		COE	Slope	r^2	COE	Slope	r^2
SA-1	26	-	-	-	0.53	0.77	0.68
SA-2	35	0.72	1.14	0.73	0.41	0.63	0.73

For the SA-1 basin, 26 events were identified (Appendix B, Table B-9). The CNI – 0.1 alternative produced a *COE* of 0.53, a slope of 0.77, and an r^2 of 0.68 (Figure 5.19). The results for this alternative were determined to be accurate and were used to represent runoff in this watershed.

A total of 35 events were identified for the SA-2 watershed (Appendix B, Table B-10). First, the CNI – 0.1 alternative was used in the modeling process. The *COE* for this run was 0.41, slope was 0.63, and the r^2 was 0.73. The CNI – 0.2 alternative was run for comparison purposes, despite the fairly decent accuracy of the CNI – 0.1 alternative. Surprisingly, this alternative more closely matched the observed runoff in this watershed. The *COE* improved to 0.72, with a slope of 1.14, and an r^2 value of 0.73 (Figure 5.20).

The overall accuracy of the runoff estimates in this watershed, along with the relatively high number of identifiable events was somewhat unexpected based on the location of this watershed and the amount of urban land cover associated with it. It is also the only watershed in this study that was more accurately represented by an alternative other than CNI – 0.1.

Figure 5.19. SA-1 NRCS CNI – 0.1 alternative.

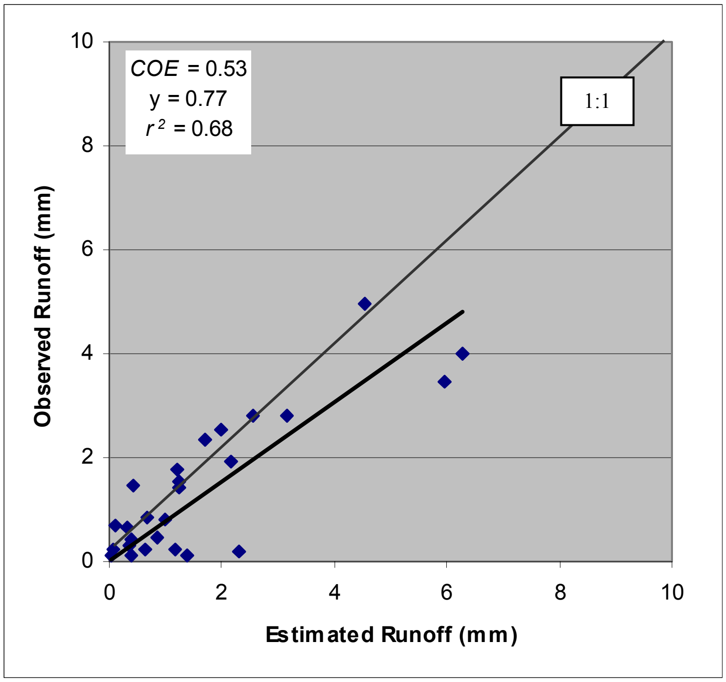
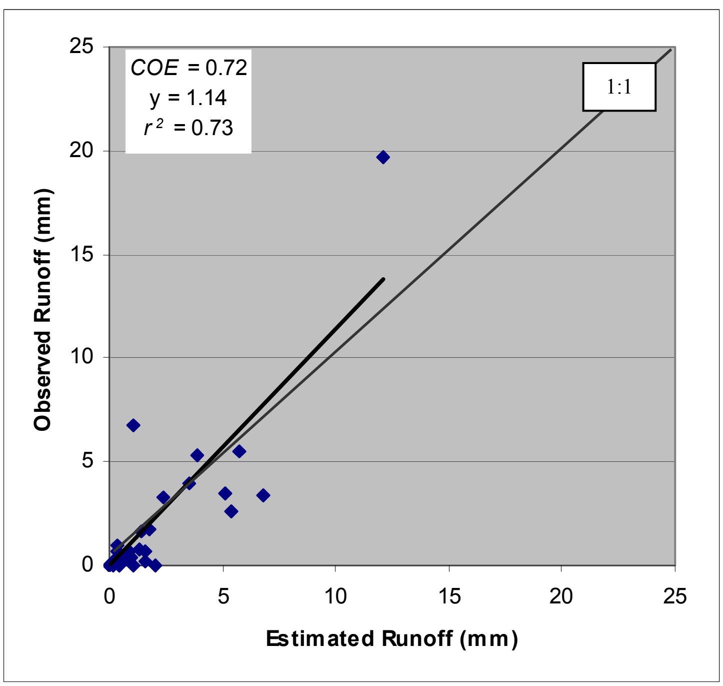
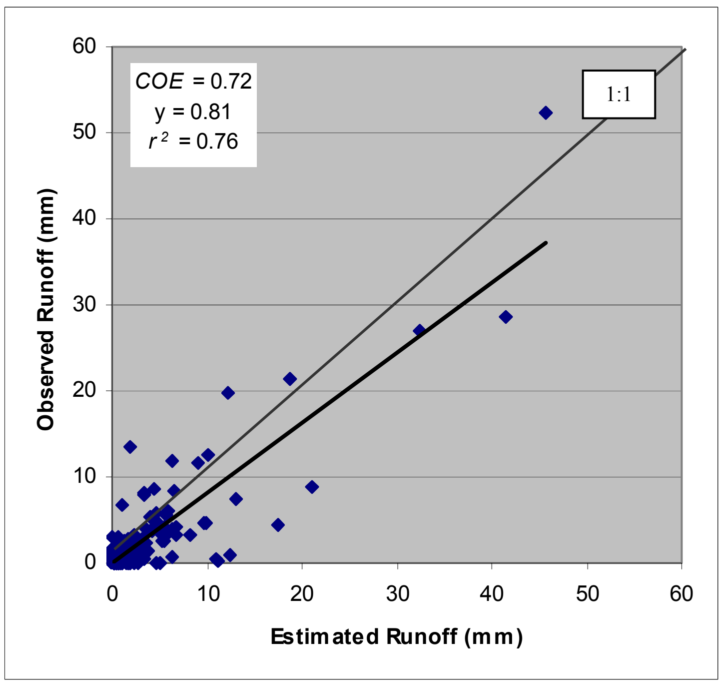


Figure 5.20. SA-2 NRCS CNI – 0.2 alternative.



5.3.5 Combined Study Area Results for 1999-2001. Finally, an overall combined statistical comparison for all events in all watersheds in this study was completed, the results of which were highly significant. The *COE* was 0.72, the slope was 0.81, and the r^2 was 0.76 (Figure 5.21). This would suggest that the methods identified for each of the watersheds in this study are relevant. The next step in this analysis was to evaluate the intra-annual variability of the runoff estimates to identify seasonal trends.

Figure 5.21. Combined study area results for 1999-2001.



5.4 Evaluation of Intra-annual Variability in NRCS Curve Number Method Runoff Estimates

As previously discussed, the CNI – 0.1 alternative was determined to be the best match for all of the watersheds in this study except the SA-2 watershed. Although the CNI – 0.1 alternative did produce significant results, the watershed was better represented by the CNI – 0.2 alternative. Results from the most statistically significant alternatives were used in evaluating the intra-annual variability between seasons and for a ranked pair analysis for the various watersheds in order to better understand runoff prediction during high and low flow events.

Although the methods used in this study are significant for the entire year, it is important to understand the significance of these alternative methods on a seasonal basis, especially during the low, moderate, and high rainfall periods. In addition, variations of CN on a seasonal basis may improve the overall performance of the model based on findings in Price (1998) and Van Mullem et al. (2002). It has been proposed that CN may change with seasonal weather pattern or land cover changes. This breakdown analysis will highlight the possible need for such variations.

The seasons identified for analysis ran from January 1st to April 25th, April 26th to September 30th, and October 1st to December 31st. In general, there were more identified events in seasons 1 and 2, before and during the growing season, than season 3, after the harvest in the dormant season.

For the ranked pair analysis, all events from all watersheds within each basin were first ranked according to rainfall into natural pairs. Statistics were then generated for the top 20%, middle 60%, and lower 20% of the events identified for each basin, which corresponds to the high, average, and low rainfall events.

5.4.1 Trinity River Basin. The CNI – 0.1 alternative was determined to be the best match for all of the Trinity River Basin watersheds; therefore, only this alternative was used in the seasonal and ranked pair analysis for the basin.

In Trinity-1, there were 11 events in season 1, 16 events in season 2, and four events in season 3 (Table 5.8). For season 1, the *COE* was 0.41, with a slope of 0.83 and an r^2 of 0.38. NEXRAD rainfall for this season ranged from 12.03 to 56.31 mm. The estimated runoff ranged from 0.01 to 4.19 mm, whereas the filtered streamflow ranged from 0.002 to 4.02 mm.

Season 2 had a *COE* of 0.70, slope of 1.05, and an r^2 of 0.68. For this season, the rainfall ranged from 12.92 to 112.71 mm. Estimated runoff ranged from 0.02 to 4.61 mm; however, filtered streamflow, or observed runoff, ranged from 0.002 to 5.77 mm.

Season 3 showed the least satisfactory results when compared with observed runoff. This season had a *COE* of-1.17, a slope of 1.63, and an r^2 of -1.78. However, there were only four events in this season, which would help to explain the lack of statistically significant results. Also, this season comprises approximately 13% of the total rainfall for this watershed. Therefore, 87% of the rainfall for this watershed can be better explained using the CNI – 0.1 runoff equation alternative. Based on findings by Price (1998) these results may be improved by altering the CN assignment or initial abstraction ratio for the period after the growing season, *i.e.* season 3. Rainfall in this season ranged from 24.14 to 46.21 mm. The estimated runoff ranged from 0.07 to 0.54 mm. The observed runoff ranged from 0.27 to 1.60 mm.

Trinity-2 had 10 events for season 1, 18 events for season 2, and four events for season 3 (Table 5.9). Season 1 had a *COE* of 0.51, a slope of 2.31, and an r^2 of 0.85. The rainfall for this season ranged from 12.76 to 38.91 mm. Estimated runoff ranged from 0.07 to 3.28 mm. Observed runoff ranged from 0.03 to 8.08 mm.

Table 5.8. Intra-annual variability in runoff estimates for the NRCS CNI – 0.1 alternative for the Trinity-1 watershed.

Season	Identified Events	Min Runoff	Max Runoff	Min Rainfall	Max Rainfall	Min Observed Streamflow	Max Observed Streamflow	COE	Slope	r^2
Season 1	11	0.01	4.19	12.03	56.31	0.00	4.02	0.41	0.83	0.38
Season 2	16	0.02	4.61	12.92	112.71	0.00	5.77	0.70	1.05	0.68
Season 3	4	0.07	0.54	24.14	46.21	0.27	1.60	-1.17	1.63	-1.78

Table 5.9. Intra-annual variability in runoff estimates for the NRCS CNI – 0.1 alternative for the Trinity-2 watershed.

Season	Identified Events	Min Runoff	Max Runoff	Min Rainfall	Max Rainfall	Min Observed Streamflow	Max Observed Streamflow	COE	Slope	r^2
Season 1	10	0.07	3.28	12.76	38.91	0.03	8.08	0.51	2.31	0.85
Season 2	18	0.03	32.42	13.22	281.19	0.01	27.02	0.93	0.83	0.97
Season 3	4	0.27	1.71	23.9	26.21	0.01	0.51	-11.89	0.08	-0.34

Table 5.10. Intra-annual variability in runoff estimates for the NRCS CNI – 0.1 alternative for the Trinity-3 watershed.

Season	Identified Events	Min Runoff	Max Runoff	Min Rainfall	Max Rainfall	Min Observed Streamflow	Max Observed Streamflow	COE	Slope	r^2
Season 1	8	0.07	45.71	11.46	122.27	0.15	52.44	0.96	1.10	0.97
Season 2	26	0.29	21.05	12.75	247.97	0.03	11.93	-1.70	0.38	0.14
Season 3	6	0.38	41.56	17.89	228.29	0.05	28.71	0.61	0.69	0.77

Season 2 had a *COE* of 0.93, a slope of 0.83, and an r^2 of 0.97. This season had a range of rainfall from 13.22 to 281.19 mm. The estimated runoff ranged from 0.03 to 32.42 mm. The observed runoff ranged from 0.01 to 27.02 mm.

As in Trinity-1, season 3 produced the least statistically significant match between estimated and observed runoff, with a *COE* of -11.89, a slope of 0.08, and an r^2 of -0.34. Again, there were only four events identified for this season, representing 13% of the total number of events for the three year study period. The range of rainfall for this season was 23.9 to 26.21 mm. The estimated runoff ranged from 0.27 to 1.71 mm. The observed runoff ranged from 0.006 to 0.51 mm.

Trinity-3 had eight events for season 1, with a *COE* of 0.96, a slope of 1.10, and an r^2 of 0.97 (Table 5.10). The rainfall range for this season was 11.46 to 122.27 mm. The estimated runoff ranged from 0.07 to 45.71 mm. The observed runoff ranged from 0.15 to 52.44 mm.

Season 2 had 26 events, with a *COE* of -1.70, a slope of 0.38, and an r^2 of 0.14. Rainfall ranged from 12.75 to 247.97 mm. Estimated runoff ranged from 0.29 to 21.05 mm. Observed runoff ranged from 0.03 to 11.93 mm. In general, this season is statistically significant in other watersheds; however, the fact that this watershed is 80% forested could explain the less than significant results. During this time period tree foliage would increase interception and therefore prevent rainfall from becoming runoff at expected levels. Instead, a large amount of rainfall would be lost to evapotranspiration.

For the six events in season 3, the *COE* was 0.61, the slope was 0.69, and the r^2 value was 0.77. Rainfall for this season ranged from 17.89 to 228.29 mm. Estimated runoff ranged from 0.38 to 41.56 mm. Observed runoff ranged from 0.05 to 28.71 mm.

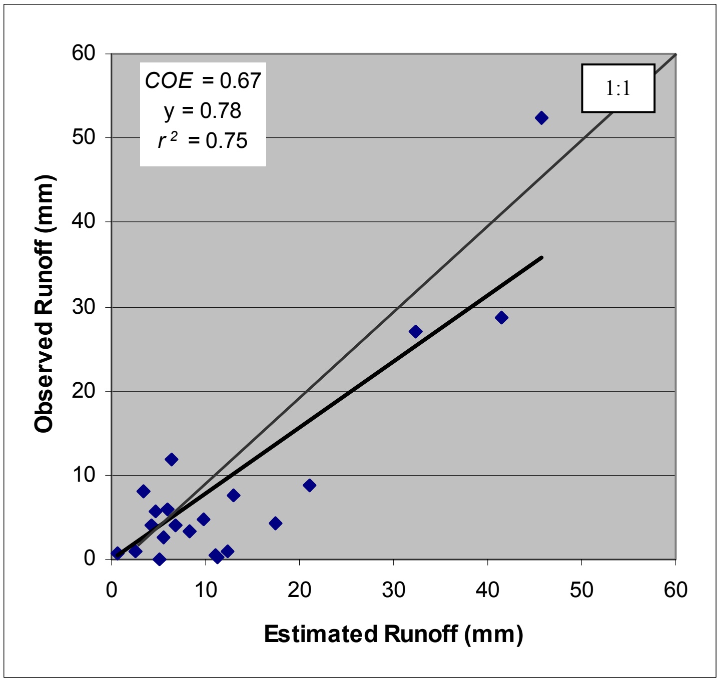
Although statistics for season 2 are not as accurate as seasons 1 and 3, this alternative is still the best overall match between modeled and observed runoff.

For the ranked pair analysis in the Trinity River Basin, the top 20% of events make up approximately 49% of the total rainfall for the three year study period (Table 5.11). For the CNI – 0.1 alternative, the *COE* was 0.67, with a slope of 0.78, and an r^2 of 0.75 (Figure 5.22). For the middle 60% of events, which make up 44% of the rainfall in the watershed, the *COE* was 0.21, the slope was 0.89, and the r^2 was 0.20. The lower 20% of events are responsible for approximately 7% of the rainfall in this watershed for the three year study period. The *COE* for this portion of the events was -1.83, the slope was 0.32, and the r^2 value was -0.42. Clearly, the model produces a more accurate representation of observed runoff in the higher flow events. Furthermore, there appears to be a direct correlation between the accuracy of model results and the amount of rainfall associated with an event. Hence the need to capture spatially accurate rainfall is critical for hydrologic modeling and proper runoff prediction.

Table 5.11. Ranked pair analysis for the Trinity River Basin watersheds.

Identified Events	Percent Rainfall	COE	Slope	r^2
Top 20%	49.3	0.67	0.78	0.75
Middle 60%	43.9	0.21	0.89	0.20
Bottom 20%	6.8	-1.83	0.32	-0.42

Figure 5.22. Trinity River Basin top 20% ranked pair analysis.



5.4.2 Red River Basin. The CNI – 0.1 alternative was again the only alternative used in the seasonal and ranked pair analysis for the Red River Basin.

For Red-1, there were nine events in season 1, nine in season 2, and four in season 3 (Table 5.12). In season 1 the *COE* was 0.67, the slope was 0.70, and the r^2 was 0.90. For this season the rainfall ranged from 11.95 to 47.43 mm. The estimated runoff ranged from 0.03 to 2.5 mm. The observed runoff ranged from 0.05 to 1.83 mm. Season 2 estimates produced better results with a *COE* of 0.98, a slope of 1.11, and an r^2 of 0.99. The rainfall for this season ranged from 14.85 to 138.93 mm. The estimated runoff ranged from 0.03 to 18.77 mm. The observed runoff ranged from 0.18 to 21.38 mm. Seasons 1 and 2 accounted for 82% of the events within this watershed. As for season 3, there were only four identified events. As in the Trinity River Basin watersheds, this season produced the poorest results. The *COE* was 0.57, the slope was1.26, and the r^2 was 0.47. The rainfall ranged from 19.21 to 30.11 mm. The estimated runoff ranged from 0.1 to 1.22 mm. The observed runoff ranged from 0.1 to 2.56 mm.

In Red-2, there were 10 events in season 1, 12 in season 2, and three in season 3 (Table 5.13). For season 1, the *COE* was 0.91, the slope was 0.85, and the r^2 was 0.94. The range of rainfall was 12.14 to 53.10 mm. The estimated runoff ranged from 0.04 to 4.31 mm. The observed runoff ranged from 0.0007 to 3.67 mm.

In season 2, the *COE* was -0.94, the slope was 0.57, and the r^2 was -0.65. The rainfall range was 18.73 to 89.69 mm. The estimated runoff ranged from 0.02 to 1.99 mm. The observed runoff ranged from 0.02 to 1.39 mm.

For season 3, the *COE* was -0.37, slope was 0.72, and the r^2 was -0.94. The rainfall ranged from 11.55 to 81.56 mm. The estimated runoff ranged from 0.01 to 1.1 mm. The observed runoff ranged from 0.003 to 1.22 mm.

Estimates for the top 20% of events, responsible for 44% of rainfall in the basin, had a *COE* of 0.97, a slope of 1.10, and an r^2 of 0.98 (Figure 5.23). For the middle 60%, the *COE* was -0.09, slope was 0.64, and the r^2 was 0.10. The lower 20% of events had a *COE* of -0.04, a slope of 1.04, and an r^2 of -0.15 (Table 5.14). The same correlation between the amount of rainfall and the accuracy of modeled rainfall estimates seen in the Trinity River Basin was seen in the Red River Basin.

Table 5.12. Intra-annual variability in runoff estimates for the NRCS CNI – 0.1 alternative for the Red-1 watershed.

Season	Identified Events	Min Runoff	Max Runoff	Min Rainfall	Max Rainfall	Min Observed Streamflow	Max Observed Streamflow	COE	Slope	r^2
Season 1	9	0.03	2.5	11.95	47.43	0.05	1.83	0.69	0.70	0.90
Season 2	9	0.03	18.77	14.85	138.93	0.18	21.38	0.98	1.11	0.99
Season 3	4	0.1	1.22	19.21	30.11	0.10	2.56	0.57	1.26	0.47

Table 5.13. Intra-annual variability in runoff estimates for the NRCS CNI – 0.1 alternative for the Red-2 watershed.

Season	Identified Events	Min Runoff	Max Runoff	Min Rainfall	Max Rainfall	Min Observed Streamflow	Max Observed Streamflow	COE	Slope	r^2
Season 1	10	0.04	4.31	12.14	53.1	0.00	3.67	0.91	0.85	0.94
Season 2	12	0.02	1.99	18.73	89.69	0.02	1.39	-0.94	0.57	-0.65
Season 3	3	0.01	1.1	11.55	81.56	0.00	1.22	-0.37	0.72	-0.94

Figure 5.23. Red River Basin top 20% ranked pair analysis.

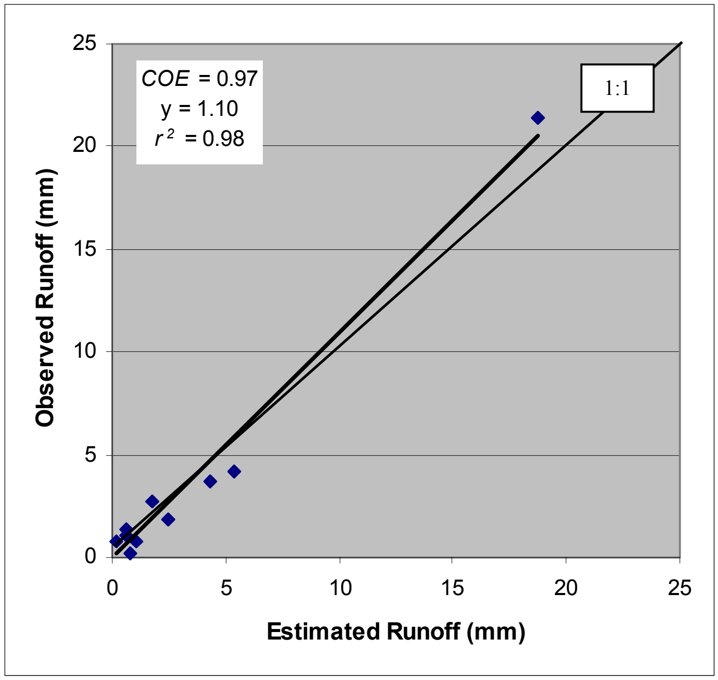


Table 5.14. Ranked pair analysis for the Red River Basin watersheds.

Identified Events	Percent Rainfall	COE	Slope	r^2
Top 20%	43.5	0.97	1.10	0.98
Middle 60%	46.9	-0.09	0.64	0.10
Bottom 20%	9.6	-0.04	1.04	-0.15

5.4.3 Lower Colorado River Basin. Of the three watersheds initially identified for this basin, two were explained by the results of the CNI – 0.1 model alternative. The other watershed, LCR-1, was eliminated from additional analysis based on poor results and various additional issues that could not be resolved.

For LCR-2, the results for seasons 1 and 3 were not considered to be extremely accurate; however, season 2 comprises 60% of all events in this watershed (Table 5.15). There were seven events in season 1, 18 in season 2, and five in season 3. Season 1 had a *COE* of -6.31, a slope of 0.37, and an r^2 of -0.15. The rainfall range for this season was 16.55 to 43.15 mm. The estimated runoff ranged from 0.12 to 3.89 mm. The observed runoff ranged from 0.21 to 1.46 mm. The small number of events and low rainfall associated with them would explain the less than significant results. Not only is a statistical analysis difficult with such a small number of samples, but this model produces more significant results with the higher rainfall events.

Season 2 had a *COE* of 0.62, a slope of 0.76, and an r^2 of 0.70. Rainfall for this season ranged from 10.84 to 88.54 mm. The estimated runoff ranged from 0.01 to 10 mm. Observed runoff ranged from 0.005 to 12.49 mm.

Season 3 had a *COE* of -1.63, a slope of 0.81, and an r^2 of -1.90. The range of rainfall was from 17.6 1 to 36.02 mm. The estimated runoff ranged from 0.28 to 0.65 mm. The observed runoff ranged from 0.27 to 0.68 mm.

In LCR-3, there were six events in each of the first two seasons and three events in season 3 (Table 5.16). The results for season 2, which make up 40% of the events identified for this watershed, were considered to be relatively accurate. The *COE* for season 2 was 0.89, the slope was 1.18, and the r^2 was 0.89. The range for rainfall in this season was 16.45 to 69.55 mm. The estimated runoff range was 0.1 to 9.03 mm. The observed runoff ranged from 0.06 to 11.68 mm.

For season 3, which was only slightly less accurate, and accounts for 20% of the total events, the *COE* was 0.51, the slope was 1.52, and the r^2 was 0.50. In this season, the rainfall ranged from 16.44 to 46.87 mm. Estimated runoff ranged from 0.02 to 0.57 mm. The observed runoff ranged from 0.03 to 0.98 mm.

Table 5.15. Intra-annual variability in runoff estimates for the NRCS CNI – 0.1 alternative for the LCR-2 watershed.

Season	Identified Events	Min Runoff	Max Runoff	Min Rainfall	Max Rainfall	Min Observed Streamflow	Max Observed Streamflow	COE	Slope	r^2
Season 1	7	0.12	3.89	16.55	43.15	0.21	1.46	-6.31	0.37	-0.15
Season 2	18	0.01	10	10.84	88.54	0.00	12.49	0.62	0.76	0.70
Season 3	5	0.28	0.65	17.61	36.02	0.27	0.68	-1.63	0.81	-1.90

Table 5.16. Intra-annual variability in runoff estimates for the NRCS CNI – 0.1 alternative for the LCR-3 watershed.

Season	Identified Events	Min Runoff	Max Runoff	Min Rainfall	Max Rainfall	Min Observed Streamflow	Max Observed Streamflow	COE	Slope	r^2
Season 1	6	0.03	1.44	14.58	46.85	0.17	2.27	-0.07	0.91	-0.27
Season 2	6	0.10	9.03	16.45	69.55	0.06	11.68	0.89	1.18	0.89
Season 3	3	0.02	0.57	16.44	46.87	0.03	0.98	0.51	1.52	0.50

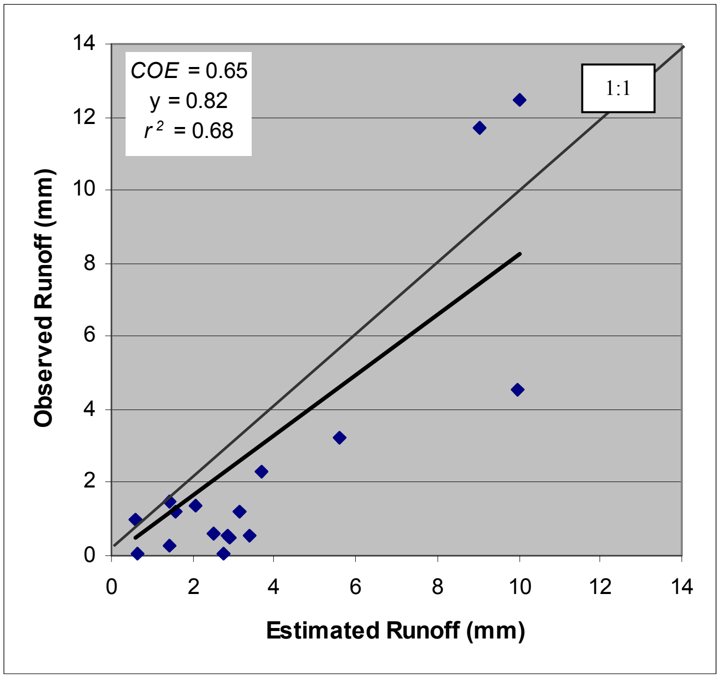
Season 1 was the least accurate with a *COE* of -0.07, a slope of 0.91, and an r^2 of -0.27. The rainfall for this season ranged from 14.58 to 46.85 mm. The estimated runoff ranged from 0.03 to 1.44 mm. The observed runoff ranged from 0.17 to 2.27 mm. Again, the small number of events and low rainfall associated with them would explain the less than significant results.

In the ranked pair analysis, the top 20% of events accounted for 37% of the total rainfall in the basin (Table 5.17). The results for this portion of the events had a *COE* of 0.65, a slope of 0.82, and an r^2 of 0.68 (Figure 5.24). The middle 60% had a *COE* of -1.50, a slope of 0.40, and an r^2 of 0.12. The lower 20% of events had a *COE* of -0.77, a slope of 0.39, and an r^2 of -0.56.

Table 5.17. Ranked pair analysis for the Lower Colorado River Basin watersheds.

Identified Events	Percent Rainfall	COE	Slope	r^2
Top 20%	37.4	0.65	0.82	0.68
Middle 60%	53.0	-1.50	0.40	0.12
Bottom 20%	9.6	-0.77	0.39	-0.56

Figure 5.24. Lower Colorado River Basin top 20% ranked pair analysis.



5.4.4 San Antonio River Basin. The CNI – 0.1 results were used for the SA-1 watershed, whereas the CNI – 0.2 results were used for SA-2 in the additional seasonal and ranked pair analysis in this basin.

The seasonal results for SA-1 were as expected. There were eight events in season 1, 16 events in season 2, and two events in season 3 (Table 5.18). Seasons 1 and 2 were fairly well represented, whereas season 3 was not. The *COE* for season 1 was 0.75, the slope was 1.25, and the r^2 was 0.86. The rainfall range was 11.53 to 51.35 mm. The estimated runoff ranged from 0.11 to 1.97 mm. The observed runoff ranged from 0.41 to 2.54 mm.

The statistics for season 2 were also fairly accurate. The *COE* was 0.54, the slope was 0.72, and the r^2 value of 0.76. The rainfall range for this season was 13.73 to 89.07 mm.

The estimated runoff range was 0.05 to 6.28 mm. The observed runoff ranged from 0.10 to 4.96 mm.

Season 3, on the other hand, had a *COE* of -4.92, a slope of 0.45, and an r^2 of -0.22. The rainfall range was 36.82 to 37.36 mm. The estimated runoff ranged from 0.42 to 2.17 mm. The observed runoff ranged from 1.48 to 1.92 mm. This season was composed of only two events (8%), which would help to explain the less than accurate comparison results.

Again, the seasonal accuracy for SA-2 was as expected (Table 5.19). Season 1 had 11 events, with a *COE* of 0.96, a slope of 0.96, and an r^2 of 0.96. The rainfall range for this season was 10.7 to 64.75 mm. The estimated runoff range was 0.03 to 5.75 mm. The observed runoff ranged from 0.05 to 5.50 mm.

Season 2 had 19 events, with a *COE* of 0.77, a slope of 1.15, and an r^2 of 0.77. For this season, the rainfall ranged from 12.11 to 145.93 mm. The estimated runoff ranged from 0.01 to 12.11 mm. The observed runoff ranged from 0.01 to 19.69 mm.

Season 3, accounting for only 14% of the events in this watershed, had five events with a *COE* of 0.13, a slope of 1.72, and an r^2 value of 0.09. The rainfall range for this season was 25.11 to 51.78 mm. The estimated runoff ranged from 0.46 to 2.4 mm. The observed runoff ranged from 0.01 to 6.77 mm.

Table 5.18. Intra-annual variability in runoff estimates for the NRCS CNI – 0.1 alternative for the SA-1 watershed.

Season	Identified Events	Min Runoff	Max Runoff	Min Rainfall	Max Rainfall	Min Observed Streamflow	Max Observed Streamflow	COE	Slope	r^2
Season 1	8	0.11	1.97	11.53	51.35	0.41	2.54	0.75	1.25	0.86
Season 2	16	0.05	6.28	13.73	89.07	0.10	4.96	0.54	0.72	0.76
Season 3	2	0.42	2.17	36.82	37.36	1.48	1.92	-4.92	0.45	-0.22

Table 5.19. Intra-annual variability in runoff estimates for the NRCS CNI – 0.2 alternative for the SA-2 watershed.

Season	Identified Events	Min Runoff	Max Runoff	Min Rainfall	Max Rainfall	Min Observed Streamflow	Max Observed Streamflow	COE	Slope	r^2
Season 1	11	0.03	5.75	10.7	64.75	0.05	5.50	0.96	0.96	0.96
Season 2	19	0.01	12.11	12.11	145.93	0.01	19.69	0.77	1.15	0.77
Season 3	5	0.46	2.4	25.11	51.78	0.01	6.77	0.13	1.72	0.09

The ranked pair analysis for this study was somewhat different, in that the CNI – 0.1 runoff estimates were used for SA-1 and CNI – 0.2 estimates were used for SA-2 (Table 5.20). These events were ranked according to rainfall totals, and the top 20%, middle 60%, and lower 20% of events were then evaluated. Again, the top 20%, responsible for approximately 40% of the rainfall in the basin, produced the best match between the estimated and observed runoff. The *COE* was 0.69, slope was 1.07, and r^2 was 0.67 (Figure 5.25). For the middle 60%, the *COE* was 0.39, the slope was 0.89, and the r^2 was 0.38. For the lower 20%, again with the poorest results, the *COE* was -0.26, slope was 0.79, and the r^2 was -0.24.

Table 5.20. Ranked pair analysis for the San Antonio River Basin watersheds.

Identified Events	Percent Rainfall	COE	Slope	r^2
Top 20%	40.2	0.69	1.07	0.67
Middle 60%	51.2	0.39	0.89	0.38
Bottom 20%	8.7	-0.26	0.79	-0.24

5.4.5 Combined Intra-annual Variability Results. An overall combined ranked pair analysis of all events in all watersheds supports the conclusion that the CN method alternatives chosen in this study produce significant results for the high flow events. For the top 20% of overall events the *COE* was 0.72, the slope was 0.81, and the r^2 was 0.77 (Figure 5.26). The results from this ranked pair analysis highlight a reduced significance from the high to low rainfall events. For the middle 60% of the flow events, the *COE* was 0.21, the slope was 0.79, the r^2 was 0.24 (Figure 5.27). For the bottom 20% of events, the *COE* was -0.67, the slope was 0.54, and the r^2 was -0.33 (Figure 5.28).

Figure 5.25. San Antonio River Basin top 20% ranked pair analysis.

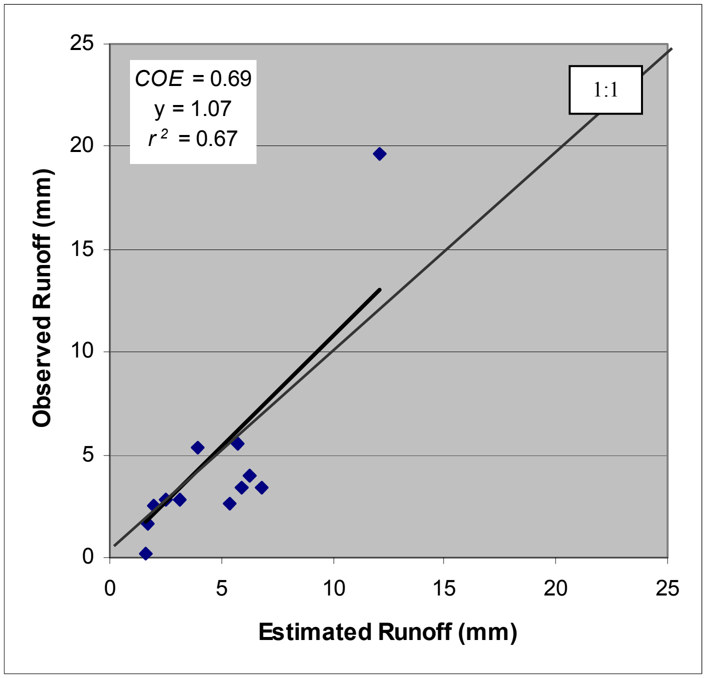


Figure 5.26. Combined ranked pair analysis for the top 20% of events.

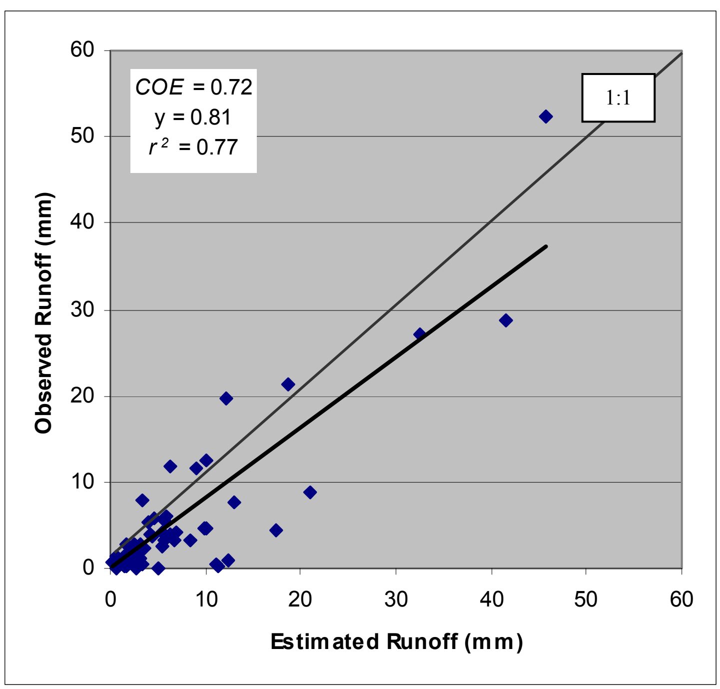


Figure 5.27. Combined ranked pair analysis for the middle 60% of events.

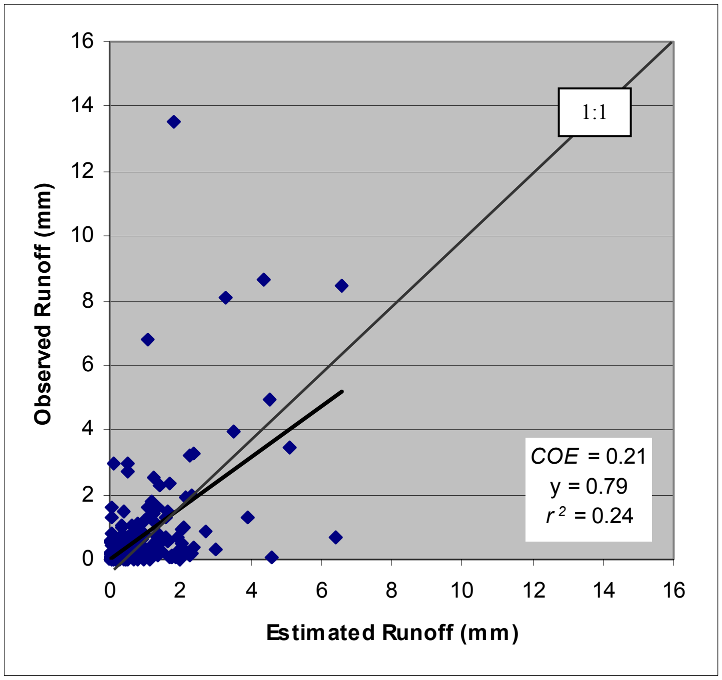
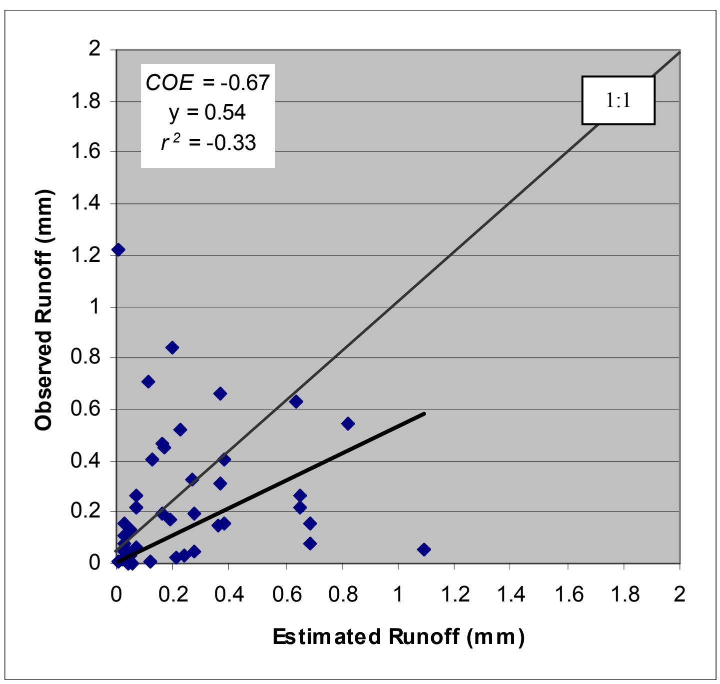


Figure 5.28. Combined ranked pair analysis for the bottom 20% of events.



VI. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The objective of this study was to evaluate several variations of the NRCS CN method for estimating runoff using NEXRAD radar rainfall data for watersheds in various agro-climatic regions of Texas.

In general, the ability of NEXRAD radar to capture the spatial variability of rainfall more accurately than the traditional raingauge networks seems to have improved the runoff estimates generated by the hydrologic modeling process. In eight out of ten watersheds in various agro-climatic regions and rainfall patterns across the state, the CNI – 0.1 method represented both annual and seasonal runoff reasonably well. In the urban SA-2 watershed, the CNI – 0.2 method was chosen as the most representative method. This appears to be true even in situations where the point comparison between raingauge and NEXRAD rainfall data is less than favorable. In the Red-2 watershed for instance, in spite of the fairly insignificant point comparison between raingauge and NEXRAD rainfall data, the model results for the watershed using the NEXRAD data seem to be statistically significant over the course of the study period. Also, in some areas where the NEXRAD modeled results seem to be insignificant, the results would not be improved with the use of raingauge data. In the LCR-1 watershed the combination of missing data, inactive stations, and apparent inaccuracy and inconsistency in the measurement of raingauge data suggest that using this as a source of rainfall inputs would not improve model results.

Altering inputs to the CN equation seemed to further improve runoff estimates. Traditionally, 0.2 would have been used for the I_a ratio with all CNs, and CNII would be the average CN value used. For this study, in almost every instance, the CNI – 0.1 alternative produced the most statistically significant results. Because CNI is used to represent a dry antecedent soil moisture condition, the use of CNII would have caused an overestimation of total runoff. In addition, the CNI – 0.2 alternative would not have produced results that were as statistically significant as the CNI – 0.1 alternative. The change in I_a ratio from 0.2 to 0.1 allows for more runoff by decreasing the total initial abstractions. The only instance in which the CNI – 0.1 alternative did not produce the most accurate results was in the SA-2 watershed. In this case, the CNI – 0.2 alternative was most appropriate. This would suggest that there was an increase in initial abstractions in this watershed. This is to be expected based on the location of this watershed in the basin and thereby the land cover associated with it. This watershed is located in the San Antonio, Texas urban area. One would expect more detention of runoff in this setting, as opposed to the relatively uninhibited flow of runoff in the other watersheds in this study.

In general, the results of the intra-annual variability analysis indicate a need to adjust the CN value and/or the I_a ratio during the period after the growing season. The results for the periods before and during the growing season appear to be significant for most areas. The exception to this might be in areas where the land cover would interfere with runoff, such as forested areas. In these areas, there may be a need to further adjust variables during the growing season.

For the ranked pair analysis, the top 20% of events were responsible for 37 – 49 % of the runoff for the watersheds in this analysis, including the flood events. Results from the ranked pair analysis for this portion of the identified events were highly significant. This would suggest that the methods identified in this study produce results that could be used in flood prediction applications.

Therefore, based on the findings of this research, the use of a CN value for dry antecedent soil moisture conditions with a reduced initial abstraction ratio should produce a fairly statistically significant representation of runoff in most areas when using NEXRAD radar rainfall estimates. This appears to be the case in all agro-climatic regions of the state. However, the use of the 0.2 I_a ratio with this same CN value appears to be more representative of areas with increased initial abstractions, such as would be expected in urban settings. It should also be noted that this appears to apply more specifically to higher rainfall events, which could make this information useful to flood prediction and mitigation in the future.

6.2 Recommendations

Future research endeavors should concentrate on issues associated with both the CN assignment and bias correction for NEXRAD radar rainfall data. First, an effort to improve the land cover input data is needed. This dataset needs to be current with the rainfall data used. In addition, a ground-truthing effort is needed. This would help to prevent inaccurate CN assignments early in the modeling process. Also, as noted by Price (1998) and Van Mullem et al. (2002), there is a need to develop a seasonal variation for the CN assignment. As evidenced by this research, there may be little variation before and during the growing season, except in forested areas; however, there is a potential need to increase CN values after the growing season during the winter months when ground cover has decreased. Also, NEXRAD rainfall data must be compared to available raingauge data to determine the need for bias correction.

Although the CN method is well documented and widely used, there is clearly a need to use this as a guideline and interpret inputs on a more local and regional level combined with seasonal variation. In addition, there is a need to vigilantly scrutinize the NEXRAD rainfall data before use in a hydrologic model. However, the use of this data in the CN method has been shown here to produce statistically significant results when used in a modified CN model. The radar is able to capture the spatial variability associated with rainfall better than the current raingauge networks. If corrected and used properly this data appears to generate improved modeling results and do so in a near real-time fashion, thereby improving the information available to water resource managers. This correction could be accomplished with the use of data from the near real-time airport raingauge stations that are currently available.

The methods outlined in this research also need to be applied to areas of more mixed and complex land use patterns to determine the usefulness of this approach in all areas of the state. Once this method can be validated, the data processing can be automated and posted on the World Wide Web. This would provide a source of real-time information for water resource managers and decision makers that is not currently available.

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APPENDIX A

DAILY COMPARISON OF RAINGAUGE AND NEXRAD RAINFALL DATA FOR 1999 – 2001

Table A-1. Raingauge and NEXRAD comparison for the Trinity-1 watershed.

Station	NWS Raingauge Station ID	NEXRAD Station (HRAP ID)	Distance to Watershed (km)	COE	Slope	r^2
1	410271	556266	0.00	0.60	0.82	0.64
2	414517	561261	0.00	0.56	0.74	0.59
3	416331	563268	1.53	0.79	0.84	0.79
4	416641	546265	7.68	0.41	0.59	0.44
5	410313	549270	9.36	0.60	0.72	0.61
6	416636	547264	6.45	0.03	0.50	0.23
7	413668	552256	15.78	0.74	0.81	0.74

Table A-2. Raingauge and NEXRAD comparison for the Trinity-2 watershed.

Station	NWS Raingauge Station ID	NEXRAD Station (HRAP ID)	Distance to Watershed (km)	COE	Slope	r^2
1	415477	624204	0.00	0.37	1.06	0.63
2	411596	621213	15.56	0.61	0.95	0.69

Table A-3. Raingauge and NEXRAD comparison for the Trinity-3 watershed.

Station	NWS Raingauge Station ID	NEXRAD Station (HRAP ID)	Distance to Watershed (km)	COE	Slope	r^2
1	415271	649202	0.66	0.69	0.90	0.72

Table A-4. Raingauge and NEXRAD comparison for the Red-1 watershed.

Station	NWS Raingauge Station ID	NEXRAD Station (HRAP ID)	Distance to Watershed (km)	COE	Slope	r^2
1	412621	505272	0.00	0.59	0.59	0.59
2	416742	509272	0.00	0.60	0.73	0.61
3	415086	508274	0.00	0.44	0.76	0.53
4	416740	509278	0.00	0.57	0.68	0.58

Table A-5. Raingauge and NEXRAD comparison for the Red-2 watershed.

Station	NWS Raingauge Station ID	NEXRAD Station (HRAP ID)	Distance to Watershed (km)	COE	Slope	r^2
1	417060	505266	0.00	-0.38	0.51	0.17
2	413828	510267	0.00	0.34	0.68	0.44
3	418468	507264	4.68	0.38	0.65	0.44

Table A-6. Raingauge and NEXRAD comparison for the LCR-1 watershed.

Station	NWS Raingauge Station ID	NEXRAD Station (HRAP ID)	Distance to Watershed (km)	COE	Slope	r^2
1	415822	529192	0.00	0.08	0.65	0.33
2	418449	509180	16.28	-0.01	0.56	0.26

Table A-7. Raingauge and NEXRAD comparison for the LCR-2 watershed.

Station	NWS Raingauge Station ID	NEXRAD Station (HRAP ID)	Distance to Watershed (km)	COE	Slope	r^2
1	413954	544175	3.43	0.72	0.84	0.73
2	418877	555180	24.04	0.73	0.98	0.78

Table A-8. Raingauge and NEXRAD comparison for the LCR-3 watershed.

Station	NWS Raingauge Station ID	NEXRAD Station (HRAP ID)	Distance to Watershed (km)	COE	Slope	r^2
1	413605	558178	2.45	0.76	0.84	0.76
2	417787	566182	11.03	0.72	0.96	0.76
3	418877	555180	0.00	0.73	0.98	0.78
4	415272	557190	13.88	0.56	0.87	0.63

Table A-9. Raingauge and NEXRAD comparison for the SA-1 watershed.

Station ID	NWS Raingauge Station ID	NEXRAD Station (HRAP ID)	Distance to Watershed (km)	COE	Slope	r^2
1	418845	545157	7.91	0.56	0.96	0.68
2	417232	532163	18.68	0.31	1.02	0.60
3	415742	545160	0.00	0.65	0.82	0.68
4	414374	542168	11.61	0.54	0.89	0.63

Table A-10. Raingauge and NEXRAD comparison for the SA-2 watershed.

Station ID	NWS Raingauge Station ID	NEXRAD Station (HRAP ID)	Distance to Watershed (km)	COE	Slope	r^2
1	411215	566161	6.01	0.27	0.81	0.47
2	417945	566155	0.00	0.61	0.81	0.64

APPENDIX B

IDENTIFIED RUNOFF AND RAINFALL EVENTS FOR ALL STUDY WATERSHEDS FOR 1999-2001

Table B-1. Identified events for the Trinity-1 watershed.

Event Start Date	NEXRAD Total Rainfall (mm)	Estimated Runoff (mm)	USGS Observed Runoff (mm)
1/29/1999	37.49	0.45	0.12
3/7/1999	33.32	0.94	0.00
3/11/1999	20.39	0.01	0.18
3/18/1999	56.31	4.19	4.02
3/27/1999	23.36	0.19	0.09
4/13/1999	30.3	0.52	0.03
4/25/1999	45.05	2.1	1.01
5/1/1999	21.68	0.02	0.05
5/25/1999	112.71	4.61	5.77
6/5/1999	14.24	0.02	0.02
3/10/2000	20.74	0.19	0.00
4/16/2000	21.62	0.1	0.02
4/29/2000	53.64	0.52	2.73
5/6/2000	17.58	0.69	0.16
5/20/2000	23.99	0.15	0.00
5/27/2000	50.9	1.88	0.09
6/15/2000	12.92	0.03	0.02
6/27/2000	51.12	0.35	0.09
7/13/2000	16.37	0.12	0.01
10/29/2000	28.09	0.54	0.55
11/2/2000	34.54	0.09	0.27
11/6/2000	46.21	0.08	1.60
12/26/2000	24.14	0.07	0.79
1/28/2001	22.07	0.1	2.97
2/9/2001	12.03	0.01	0.01
2/23/2001	24.92	0.07	1.32
4/11/2001	14.42	0.03	0.16
5/4/2001	52.45	0.95	1.15
5/20/2001	26.08	0.43	0.01
6/14/2001	22.36	0.14	0.01
6/28/2001	26.96	1.12	0.01

Table B-2. Identified events for the Trinity-2 watershed.

Event Start Date	NEXRAD Total Rainfall (mm)	Estimated Runoff (mm)	USGS Observed Runoff (mm)
1/1/1999	38.91	3.28	8.08
1/22/1999	18	0.29	0.68
3/9/1999	15.12	0.07	0.06
3/13/1999	22.9	0.64	0.63
4/4/1999	23.85	0.46	0.30
4/14/1999	26.42	0.53	2.98
4/27/1999	34.7	2.75	0.87
5/10/1999	50.88	0.73	0.67
5/18/1999	13.22	0.03	0.11
5/24/1999	13.36	0.04	0.01
5/27/1999	54.18	0.82	1.14
6/23/1999	25.81	0.17	0.45
7/10/1999	81.96	6.84	4.09
10/17/1999	24.05	0.39	0.01
12/5/1999	24.03	1.71	0.04
12/12/1999	26.21	0.4	0.51
1/7/2000	33.2	0.9	0.24
3/3/2000	12.76	0.24	0.03
3/11/2000	16.64	0.23	0.52
4/11/2000	17.51	0.2	0.84
5/13/2000	15.29	0.28	0.05
5/20/2000	47.15	6.6	8.47
5/28/2000	14.09	0.36	0.15
6/10/2000	50.24	2.18	0.25
6/19/2000	33.96	1.32	0.37
9/13/2000	23.19	0.68	0.02
9/25/2000	22.41	0.82	0.01
10/7/2000	23.9	0.27	0.03
5/21/2001	17.48	0.69	0.08
5/27/2001	24.55	0.62	0.09
7/1/2001	51.62	2.3	1.96
8/27/2001	281.19	32.42	27.02

Table B-3. Identified events for the Trinity-3 watershed.

Event Start Date	NEXRAD Total Rainfall (mm)	Estimated Runoff (mm)	USGS Observed Runoff (mm)
1/23/1999	12.33	0.16	0.46
3/25/1999	12.86	0.65	0.27
3/30/1999	11.46	0.07	0.26
4/4/1999	122.27	45.71	52.44
4/15/1999	14.28	0.17	0.45
4/27/1999	22.2	1.63	0.53
5/10/1999	77.95	8.3	3.25
5/18/1999	18.36	0.39	0.29
5/26/1999	31.45	1.6	1.29
7/4/1999	109.97	3.46	7.97
7/18/1999	28.71	0.34	1.04
9/1/1999	27.34	0.29	0.10
9/9/1999	27.93	1.76	0.08
9/29/1999	62.88	12.42	0.85
10/9/1999	17.89	0.38	0.16
10/31/1999	31.33	1.91	0.71
12/13/1999	27.81	1.27	0.48
3/26/2000	19.64	0.13	0.15
4/2/2000	69.83	9.76	4.75
4/13/2000	52.88	6.4	0.69
5/2/2000	99.53	21.05	8.80
5/10/2000	32.88	4.36	8.67
5/20/2000	63.81	13.02	7.55
6/10/2000	84.06	5.93	5.96
6/19/2000	33.52	1.05	1.63
7/30/2000	84.15	11.02	0.36
8/22/2000	31.18	0.59	0.05
9/9/2000	54.47	5	0.03
9/21/2000	81.37	11.26	0.21
10/17/2000	32.25	4.6	0.05
11/3/2000	228.29	41.56	28.71
11/16/2000	51.29	1.81	13.55
5/5/2001	83.54	2.64	1.04
5/28/2001	74.27	5.46	2.59
6/15/2001	66.94	6.32	11.93
6/27/2001	62.5	0.66	0.68
8/7/2001	24.86	1.1	0.03
8/17/2001	12.75	1.09	0.05
8/27/2001	247.97	17.44	4.34
9/22/2001	45.93	2.04	0.91

Table B-4. Identified events for the Red-1 watershed.

Event Start Date	NEXRAD Total Rainfall (mm)	Estimated Runoff (mm)	USGS Observed Runoff (mm)
1/28/1999	21.54	0.04	0.44
3/27/1999	21.69	0.39	0.22
4/24/1999	13.83	0.03	0.08
4/28/1999	63.09	5.38	4.14
5/9/1999	31.03	1.28	1.11
6/10/1999	55.7	1.73	2.68
6/19/1999	138.93	18.77	21.38
8/27/1999	18.52	0.35	0.24
10/7/1999	30.11	1.22	2.56
10/29/1999	29.48	0.98	0.24
1/7/2000	13.7	0.16	0.19
2/24/2000	31.12	0.67	0.28
4/11/2000	27.22	0.25	0.08
4/22/2000	11.95	0.04	0.05
6/17/2000	21.95	0.03	0.18
7/1/2000	14.85	0.64	0.63
10/13/2000	19.21	0.1	0.10
11/23/2000	21.94	0.54	0.21
2/8/2001	23.84	0.41	0.13
2/23/2001	47.43	2.5	1.83
5/25/2001	32.71	1.34	0.60
6/22/2001	19.04	0.69	0.28

Table B-5. Identified events for the Red-2 watershed.

Event Start Date	NEXRAD Total Rainfall (mm)	Estimated Runoff (mm)	USGS Observed Runoff (mm)
3/27/1999	31.54	0.68	0.16
4/2/1999	15.54	0.05	0.03
4/28/1999	35.22	0.58	1.39
6/6/1999	89.69	0.65	1.06
6/12/1999	26.85	0.4	0.76
7/9/1999	30.31	0.47	0.14
2/24/2000	18.61	0.08	0.05
3/22/2000	53.1	4.31	3.67
4/15/2000	12.14	0.28	0.20
4/22/2000	15.34	0.04	0.00
6/1/2000	35.09	0.61	1.03
6/17/2000	34.08	0.02	0.58
10/14/2000	21.9	0.04	0.00
10/23/2000	81.56	1.1	0.79
11/23/2000	11.55	0.01	1.22
2/8/2001	14.83	0.06	0.00
2/23/2001	18.12	0.13	0.41
3/7/2001	35.16	0.21	0.81
3/23/2001	21.39	0.07	0.19
5/17/2001	21.15	0.38	0.05
6/1/2001	41.22	0.83	0.23
6/22/2001	28.75	1.15	1.37
7/14/2001	18.73	0.05	0.02
9/2/2001	24.61	0.09	0.67
9/20/2001	29.03	1.99	0.02

Table B-6. Identified events for the LCR-1 watershed.

Event Start Date	NEXRAD Total Rainfall (mm)	Estimated Runoff (mm)	USGS Observed Runoff (mm)
1/28/1999	22.26	0.69	0.73
3/11/1999	62.97	3.66	2.32
3/27/1999	17.01	0.12	0.15
4/2/1999	30.92	0.63	0.13
4/25/1999	32.03	0.91	0.18
5/3/1999	15.96	0.37	0.06
5/26/1999	32.16	1.09	0.24
6/19/1999	56.01	2.51	0.60
7/10/1999	36.39	0.88	0.67
9/8/1999	19.55	0.82	0.06
10/16/1999	16.59	0.8	0.33
10/29/1999	21.15	0.14	0.11
2/22/2000	17.58	0.06	0.17
3/28/2000	14.16	0.89	0.05
4/11/2000	31.11	1.46	0.27
4/19/2000	10.79	0.1	0.05
4/27/2000	26.04	2.06	0.50
5/19/2000	21.74	0.71	0.33
5/27/2000	18.13	0.28	0.10
6/3/2000	29.49	1.92	0.24
6/9/2000	23.38	0.09	0.24
6/17/2000	49.62	2.9	0.51
7/25/2000	12.02	0.09	0.04
9/12/2000	18.42	0.29	0.07
9/24/2000	33.29	1.35	0.18
10/15/2000	23.88	0.15	0.41
10/21/2000	35.06	0.6	0.29
2/15/2001	13.59	0.05	0.27
3/8/2001	13.85	0.08	0.05
3/11/2001	17.98	0.72	0.04
4/10/2001	19.81	0.73	0.29
4/22/2001	32.79	2.26	0.11
5/4/2001	47.13	1.55	1.20
6/23/2001	17.63	0.58	0.09
7/1/2001	20.86	0.49	0.27
8/16/2001	25.62	0.43	0.18
8/26/2001	66.57	2.05	1.36
9/18/2001	51.5	3.37	0.54

Table B-7. Identified events for the LCR-2 watershed.

Event Start Date	NEXRAD Total Rainfall (mm)	Estimated Runoff (mm)	USGS Observed Runoff (mm)
3/12/1999	16.55	0.28	0.67
3/27/1999	33.61	1.63	1.46
4/24/1999	38.19	0.64	0.68
5/9/1999	88.54	9.98	4.55
5/26/1999	51.58	1.44	1.48
6/12/1999	36.97	3.01	0.34
6/20/1999	26.82	0.81	0.95
7/10/1999	46.98	2.83	0.56
9/8/1999	14.12	0.62	0.01
10/16/1999	30.31	0.58	0.27
10/29/1999	21.56	0.28	0.45
12/11/1999	17.61	0.32	0.34
2/22/2000	36.16	2.38	0.34
2/25/2000	16.62	0.12	0.21
3/7/2000	31.07	1.38	0.42
4/11/2000	43.15	3.89	1.31
5/1/2000	62.97	10	12.49
5/12/2000	27.59	1.74	0.11
5/19/2000	10.84	0.01	0.24
5/27/2000	20.81	0.27	0.16
6/2/2000	14.36	0.06	0.37
6/9/2000	40.03	1.38	0.81
6/17/2000	26.75	0.16	0.34
9/12/2000	22.59	0.15	0.00
10/7/2000	36.02	0.65	0.36
10/15/2000	32.45	0.34	0.68
5/4/2001	41.67	2.29	3.21
5/24/2001	48.05	5.6	3.21
6/23/2001	15.27	0.3	0.36
8/14/2001	52.14	3.12	1.18

Table B-8. Identified events for the LCR-3 watershed.

Event Start Date	NEXRAD Total Rainfall (mm)	Estimated Runoff (mm)	USGS Observed Runoff (mm)
3/12/1999	14.58	0.03	1.70
10/29/1999	25.17	0.22	0.03
12/11/1999	16.44	0.02	0.38
2/22/2000	27.99	0.43	0.30
3/7/2000	46.85	1.44	0.28
3/26/2000	38.85	0.53	0.69
4/2/2000	15.67	0.29	0.17
4/11/2000	35.93	1.42	2.27
5/1/2000	69.55	9.03	11.68
5/27/2000	18.7	0.12	0.33
10/22/2000	46.87	0.57	0.98
5/20/2001	16.45	0.1	0.57
7/1/2001	36.25	0.36	0.40
8/14/2001	62.15	2.73	0.07
8/26/2001	55.79	0.62	0.06

Table B-9. Identified events for the SA-1 watershed.

Event Start Date	NEXRAD Total Rainfall (mm)	Estimated Runoff (mm)	USGS Observed Runoff (mm)
3/12/1999	15.44	0.38	0.41
3/18/1999	11.53	0.11	0.70
3/27/1999	30.18	1.23	1.41
4/24/1999	51.35	1.97	2.54
5/9/1999	55.76	2.55	2.80
5/17/1999	24.23	1.19	1.77
5/26/1999	42.45	4.53	4.96
6/12/1999	56.04	6.28	4.00
10/16/1999	37.36	2.17	1.92
2/1/2000	21.44	0.33	0.66
2/22/2000	33.24	0.99	0.80
4/11/2000	24.28	0.67	0.86
5/1/2000	29.78	1.25	1.54
5/12/2000	16.83	0.37	0.32
5/19/2000	16.99	0.65	0.22
5/27/2000	29.62	1.38	0.10
6/2/2000	18.07	0.07	0.22
6/9/2000	55.83	3.15	2.81
7/23/2000	13.73	0.05	0.13
7/30/2000	24.45	0.84	0.44
9/12/2000	26.1	0.39	0.13
9/24/2000	34.1	2.31	0.19
10/7/2000	36.82	0.42	1.48
4/15/2001	30.17	1.71	2.34
8/16/2001	23.53	1.16	0.23
8/26/2001	89.07	5.94	3.45

Table B-10. Identified events for the SA-2 watershed.

Event Start Date	NEXRAD Total Rainfall (mm)	Estimated Runoff (mm)	USGS Observed Runoff (mm)
3/12/1999	10.7	0.03	0.05
3/18/1999	17.76	0.27	0.33
3/27/1999	39.49	3.52	3.98
4/24/1999	34.65	0.15	0.13
5/9/1999	28.14	1.39	1.62
5/17/1999	15.91	0.82	0.55
6/20/1999	103	6.79	3.36
7/3/1999	21.99	0.01	0.01
7/10/1999	55.84	5.36	2.61
7/17/1999	28.78	0.35	0.97
8/23/1999	26.71	1.99	0.02
8/29/1999	12.11	0.21	0.03
10/16/1999	26.76	0.46	0.01
1/7/2000	19.25	0.49	0.34
2/1/2000	21.04	0.74	0.45
2/22/2000	28.95	0.77	0.45
4/1/2000	34.37	0.65	0.39
5/1/2000	18.79	0.37	0.66
5/19/2000	26.25	1.31	0.75
6/4/2000	28.74	0.98	0.38
6/8/2000	145.93	12.11	19.69
6/18/2000	24.01	0.88	0.64
9/12/2000	47.21	1.59	0.19
9/24/2000	21.77	0.42	0.03
10/7/2000	51.78	1.74	1.69
10/17/2000	32.13	2.4	3.25
10/21/2000	42.08	0.72	0.29
11/23/2000	25.11	1.1	6.77
2/15/2001	15.06	0.19	0.17
3/11/2001	38.29	1.6	0.65
4/22/2001	64.75	5.75	5.50
5/4/2001	72.8	3.92	5.32
5/20/2001	29.92	1.04	0.05
6/14/2001	31.72	5.13	3.48
9/22/2001	23.56	0.37	0.15

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Educational Background

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Experience

August 2001 – October 2003: Graduate Research Assistant
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February 2001 - August 2001: Student Technician
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Publications

- J. Moon, R.Srinivasan, and J.L. Hadley. Streamflow estimation using spatially distributed rainfall in the Trinity River basin. Transactions of the ASAE. (In Review).

- Salin, Victoria, Kristi H. Cleere, Jennifer L. Hadley, and Curtis F. Lard. 2002. Fire ants in Texas no picnic. Golf Course Management. http://www.gcsaa.org/gcm/2002/july02/07front.html.

Awards

- Recipient of the Texas Water Resources Institute's 2002-2003 Water Resources Research Grant , funded by the National Institute for Water Research and the U.S. Geological Survey.

- Recipient of the 2002 Vice Chancellor's Award in Excellence for Graduate Student Teaching.